Status and Future of Kaon Physics at BNL

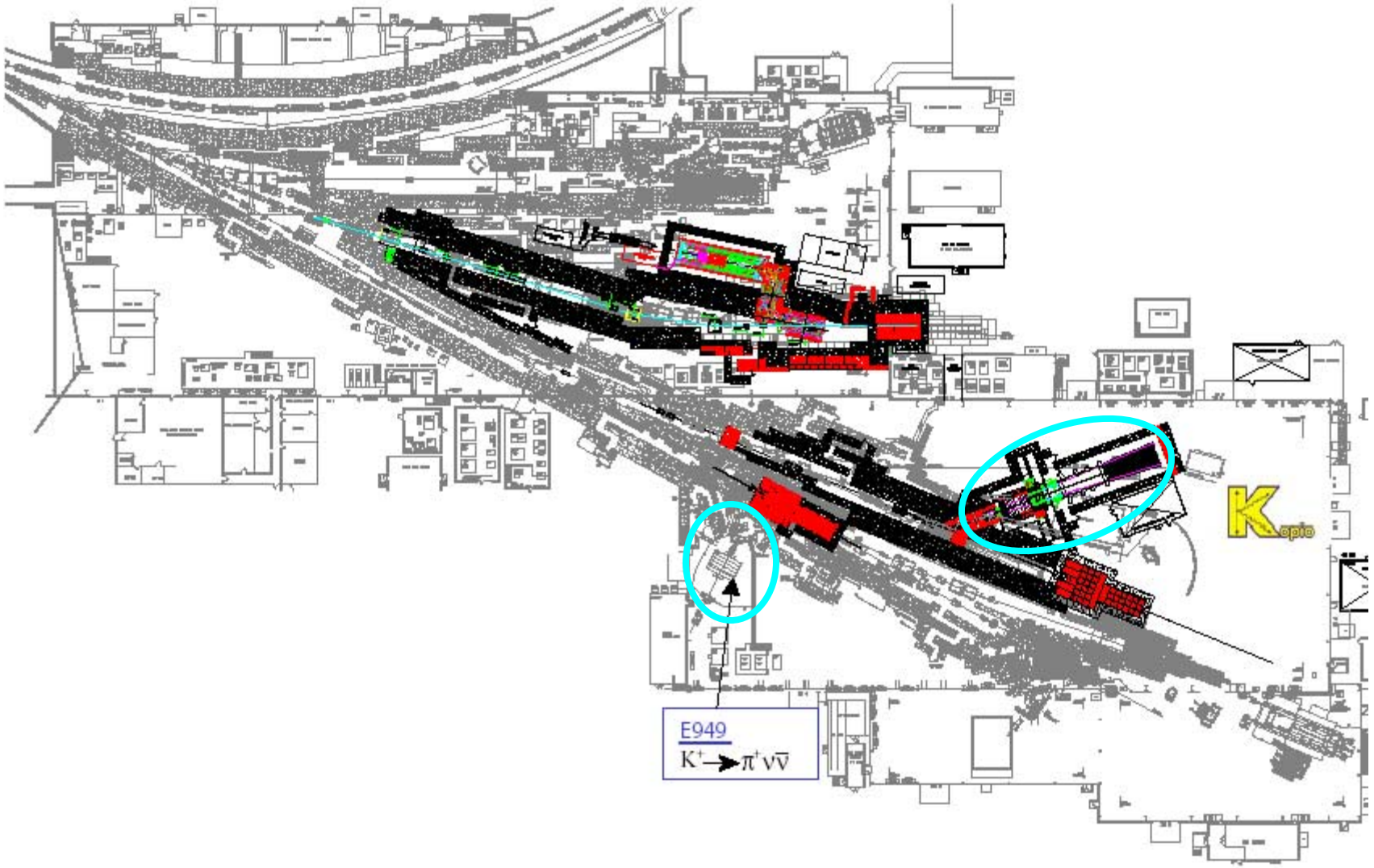
—— $K \to \pi\nu\bar{\nu}$ ——

Toshio Numao

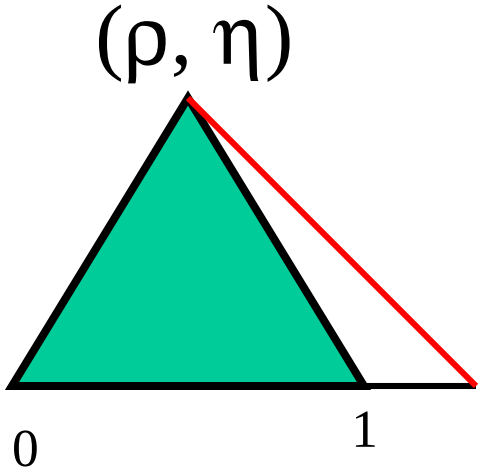
TRIUMF

October 7, 2004

AGS Experimental Hall



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$



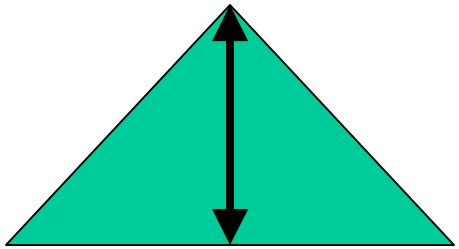
$BR \propto \eta^2 + (\rho - \rho_c)^2$

$BR(SM) = (7.8 \pm 1.2) \times 10^{-11}$

$BR(949) = (1.47\ ^{+\ 1.30}_{-\ 0.89}) \times 10^{-10}$

E949 goal ~ 10 events

$K_L^0 \to \pi^0 \nu\bar{\nu}$



cp − + +

$K_L = K_2 + \epsilon K_1 \to \pi^0 \nu\bar{\nu}$

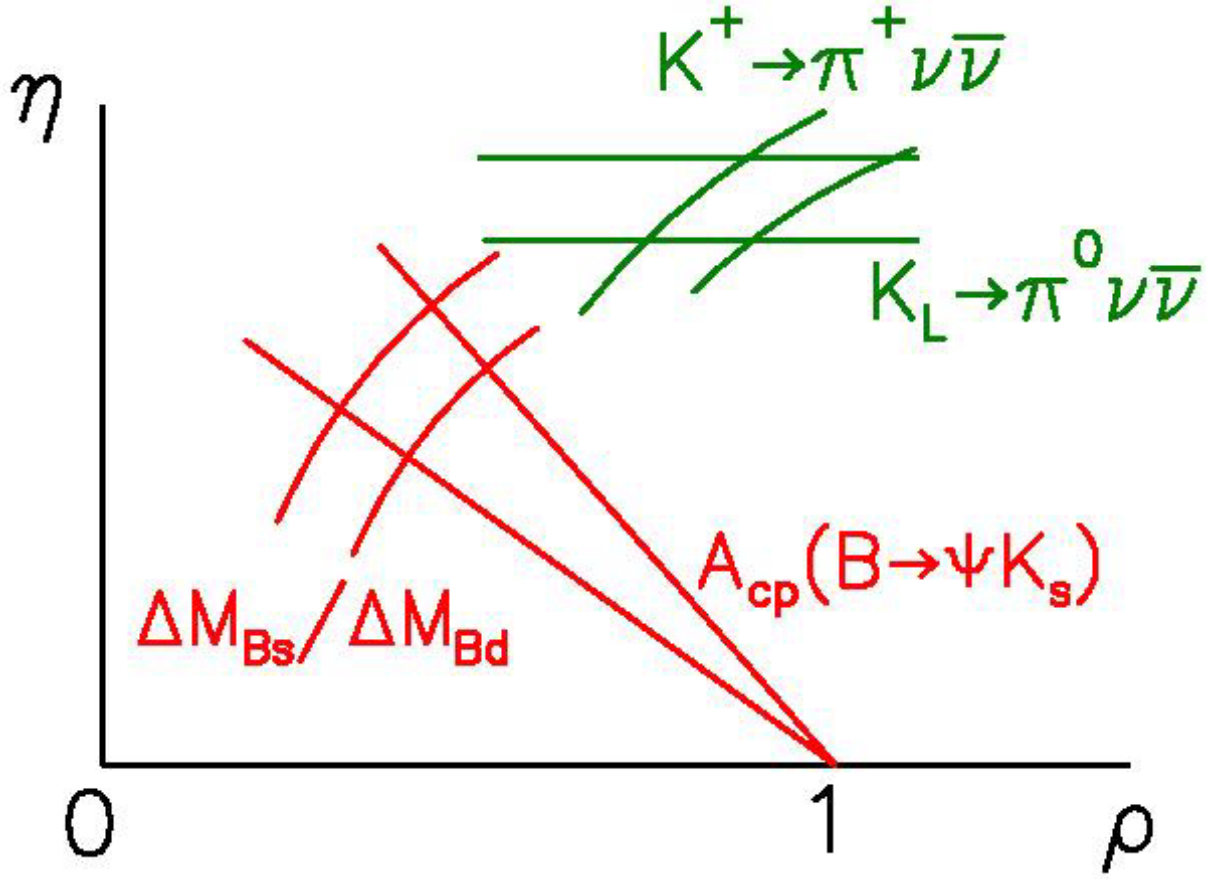
mixing $\sim 10^{-15}$

decay $\sim 3 \times 10^{-11}$

Previous search: 5.9×10^{-7} (KTEV)

KOPIO goal: 10^{-12} s.e.s., >50 events

Possible scenario



This test requires 10% measurements.

Collaborations

E787

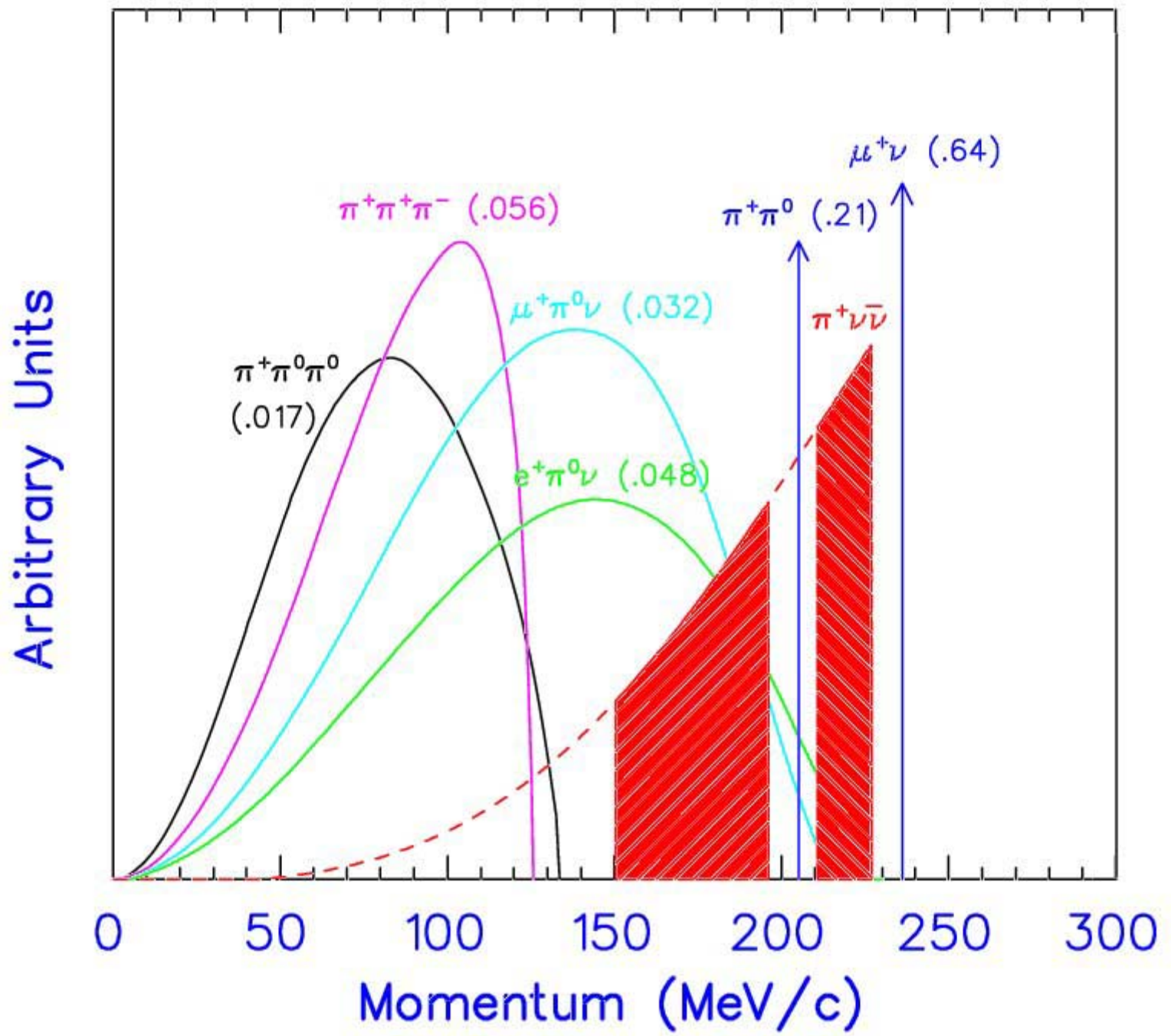
BNL, Fukui, KEK, Osaka, Princeton, TRIUMF

E949

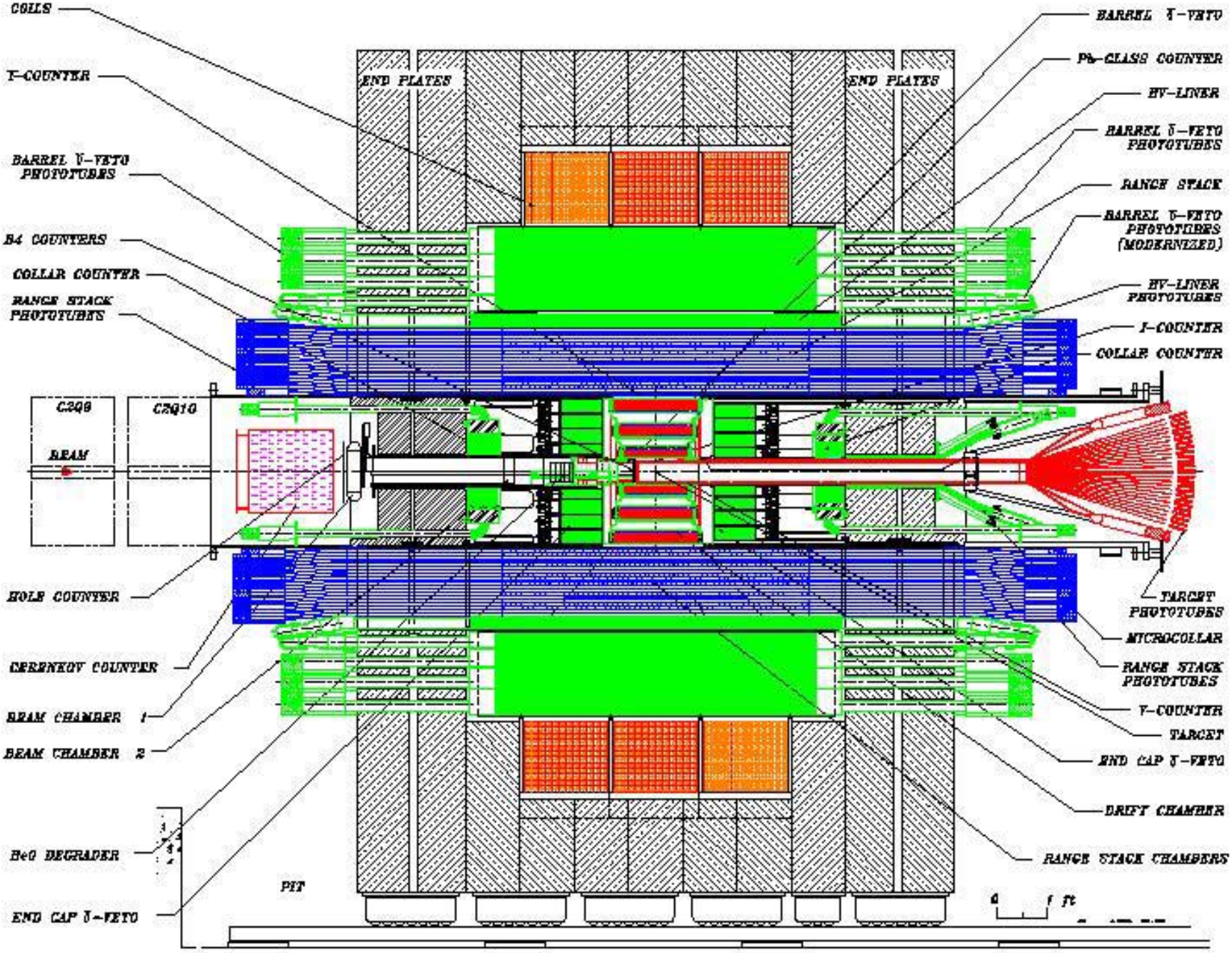
BNL, FNAL, Fukui, INR, KEK, Kyoto, New Mexico, Osaka, TRIUMF

KOPIO

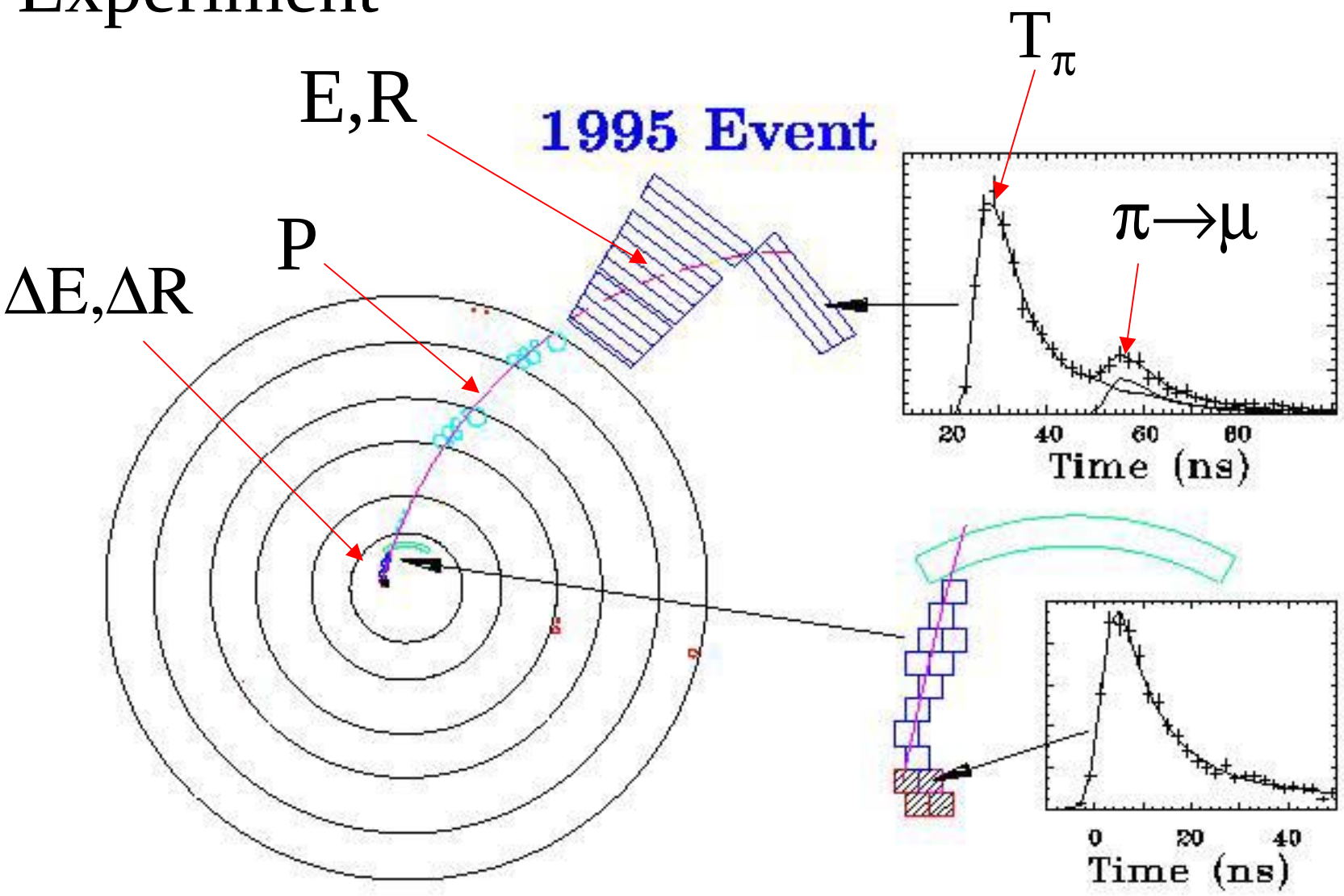
Arizona, BNL, Cincinatti, IHEP, INR, KEK, Kyoto, Montreal, New Mexico, Perugia, SUNY, TJNAF, TRIUMF, UBC, Virginia, VPI, Yale, Zurich


Arbitrary Units
$\mu^+\nu$ (.64)
$\pi^+\pi^+\pi^-$ (.056)
$\pi^+\pi^0$ (.21)
$\mu^+\pi^0\nu$ (.032)
$\pi^+\nu\bar{\nu}$
$\pi^+\pi^0\pi^0$
(.017)
$e^+\pi^0\nu$ (.048)
0
50
100
150
200
250
300
Momentum (MeV/c)

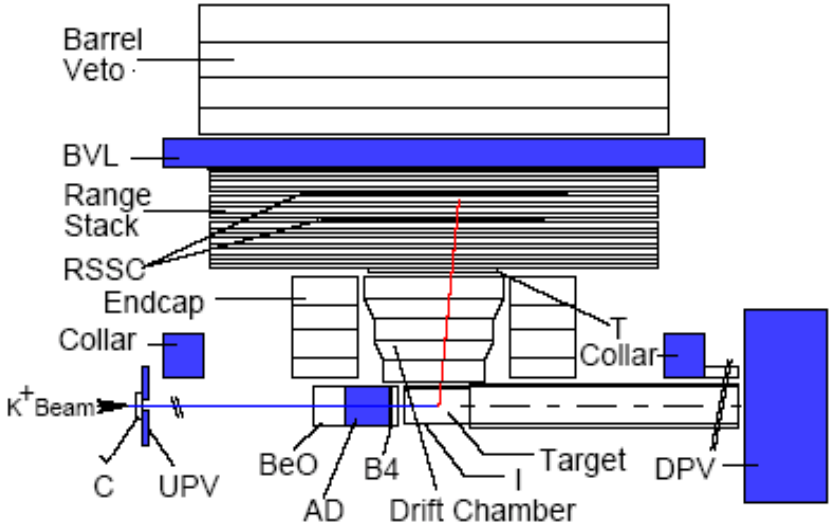
E949 Detector



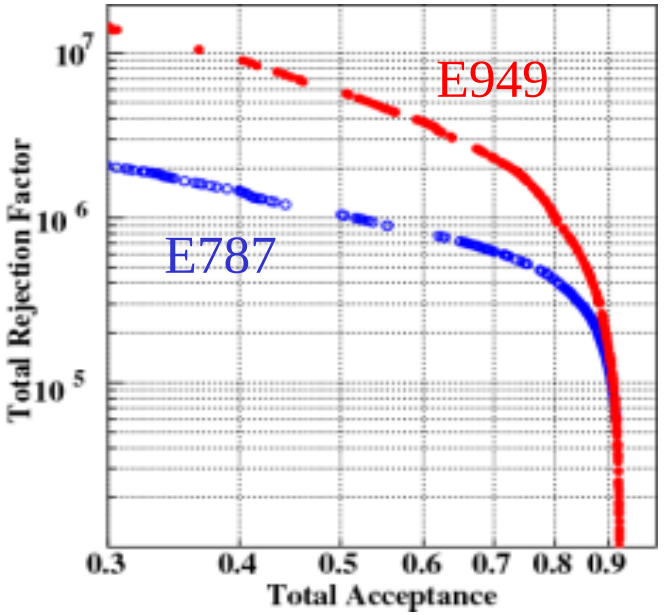
Experiment



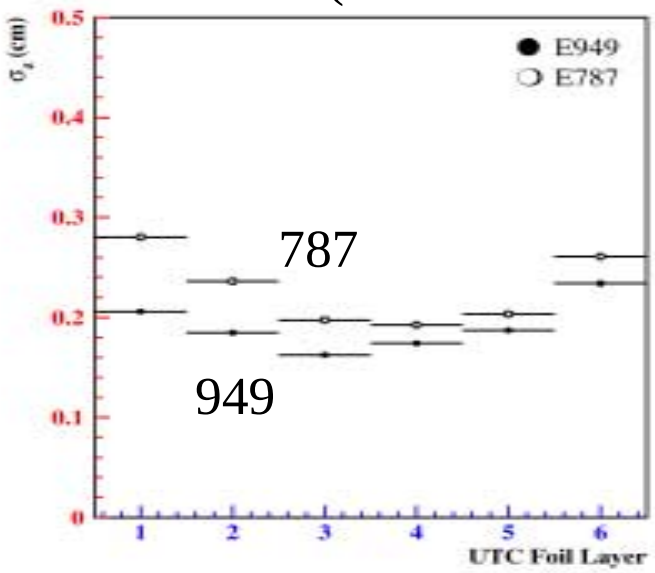
E787 → E949



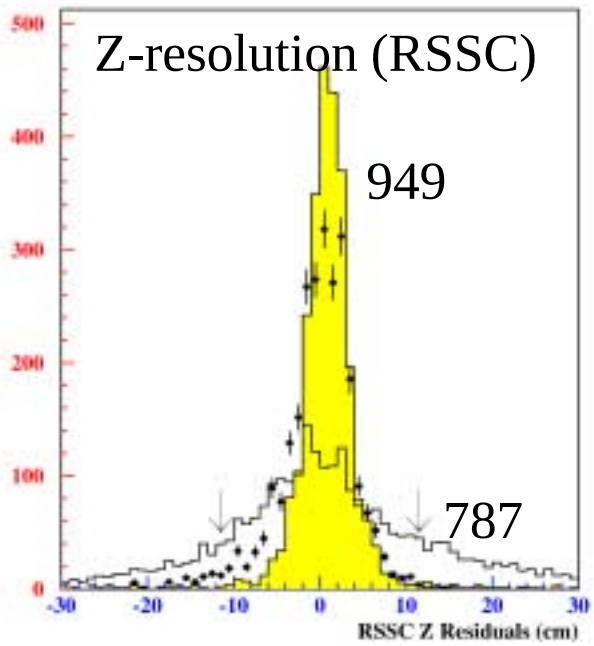
π^0 Veto power



Z resolution (Drift Chamber)

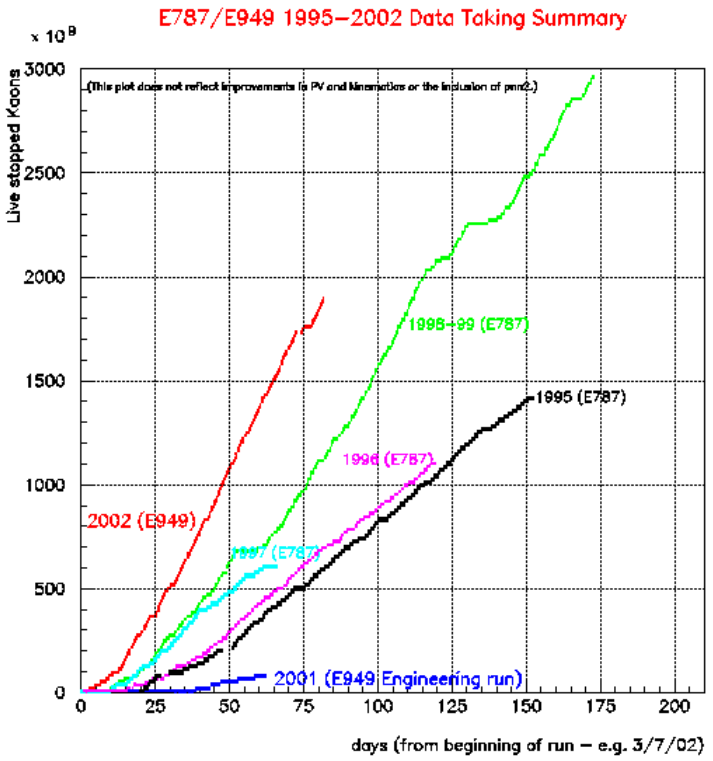


Z-resolution (RSSC)



Run Summary

	1995	1998	2002	E949
AGS(GeV)	24	24	21.5	24
spill(s)	1.4	2.2	2.2	4.1
DF(%)	41	49	41	64
P_K(MeV/c)	790	710	710	~710
K/s(MHz)	0.81	0.97	1.57	~1.6
K/π	3.8	4.0	3.1	4.0
LT	0.76	0.81	0.74	0.85
$N_K/y(10^{12})$	1.55	2.90	1.90	~10

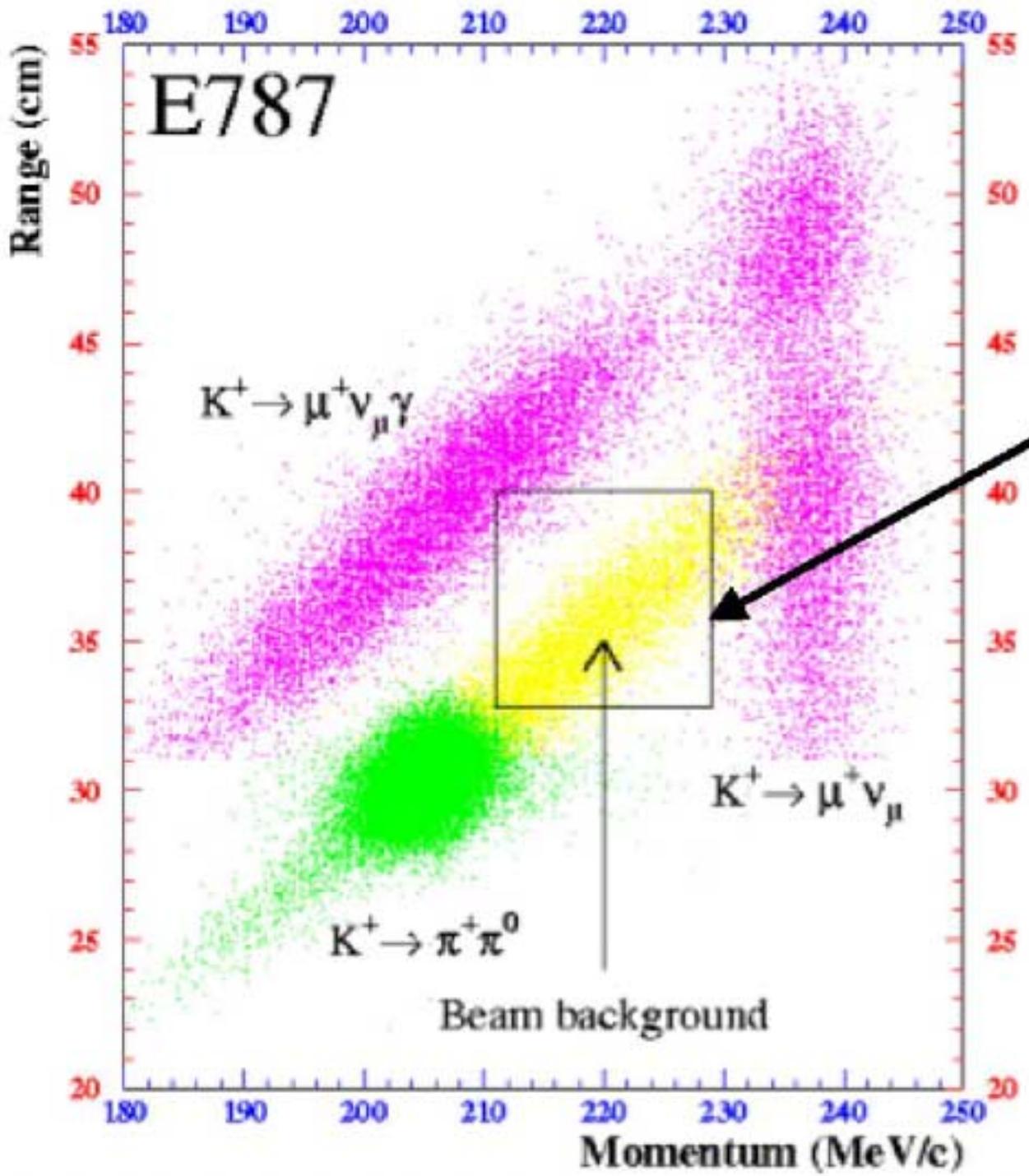


Despite PS (low DF) and separator (bad K/π) problems,
and shorter run,

-Same P,E,R resolutions (E is actually better)

-Comparable statistics

-Higher acceptance (0.20%→0.22%)



Signal Box

BG suppression

$K^+ \to \pi^+ \pi^0$: γ veto,kin
$K^+ \to \mu^+ \nu$: PID,kin
Beam : 2nd beam del.coin.

Analysis strategy

To avoid a bias:

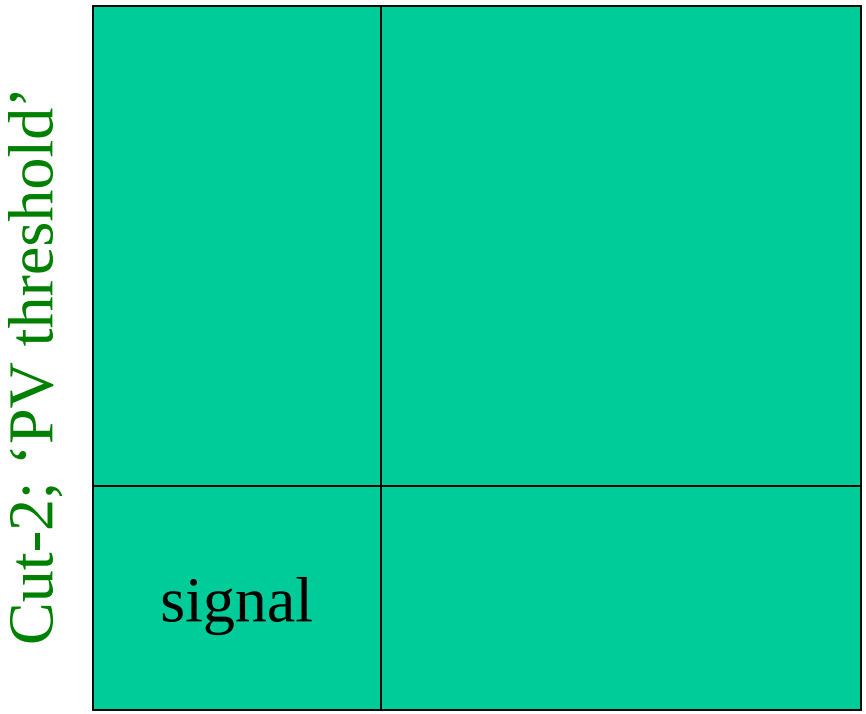
First, fix the cuts and estimate the background (1/3 data).

Use data as much as possible in the background estimates.

Bifurcated BG analysis (2/3) data.

Study the correlation.

Open the “box”.



$K_{\pi 2}$: 1=Kinematics 2=photon veto

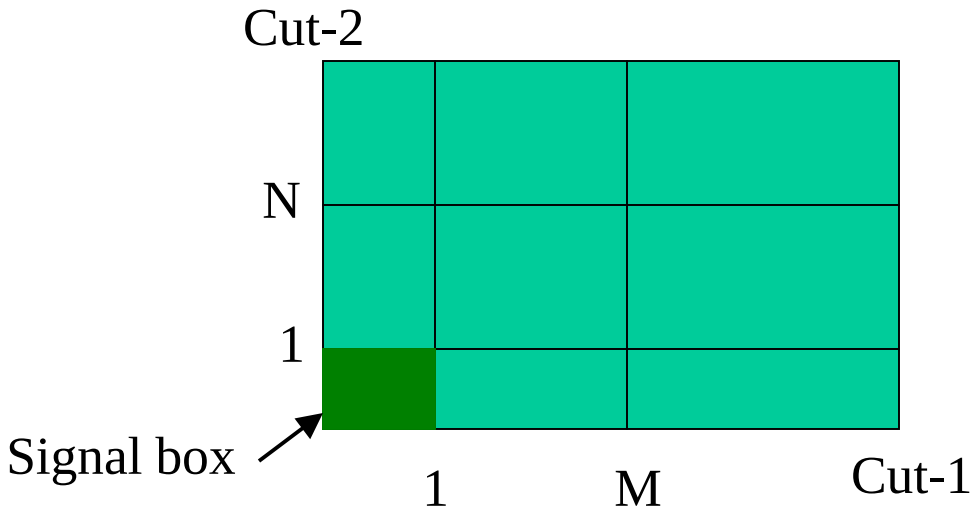
Backgrounds inside the box

Items	E949	E787
Nk(10^{12})	1.8	5.9
$K^+ \to \mu^+\nu_\mu\gamma$	0.068 ± 0.011	0.062 ± 0.045
$K^+ \to \pi^+\pi^0$	0.216 ± 0.023	0.034 ± 0.007
Beams	0.009 ± 0.003	0.025 ± 0.016
$K^+ n \to K^0 p$, $K^0 \to \pi^+ l^- \nu$	0.005 ± 0.001	0.025 ± 0.008
Total bkg (evts)	0.298 ± 0.026	0.146 ± 0.049

❖**Errors are statistical only.**

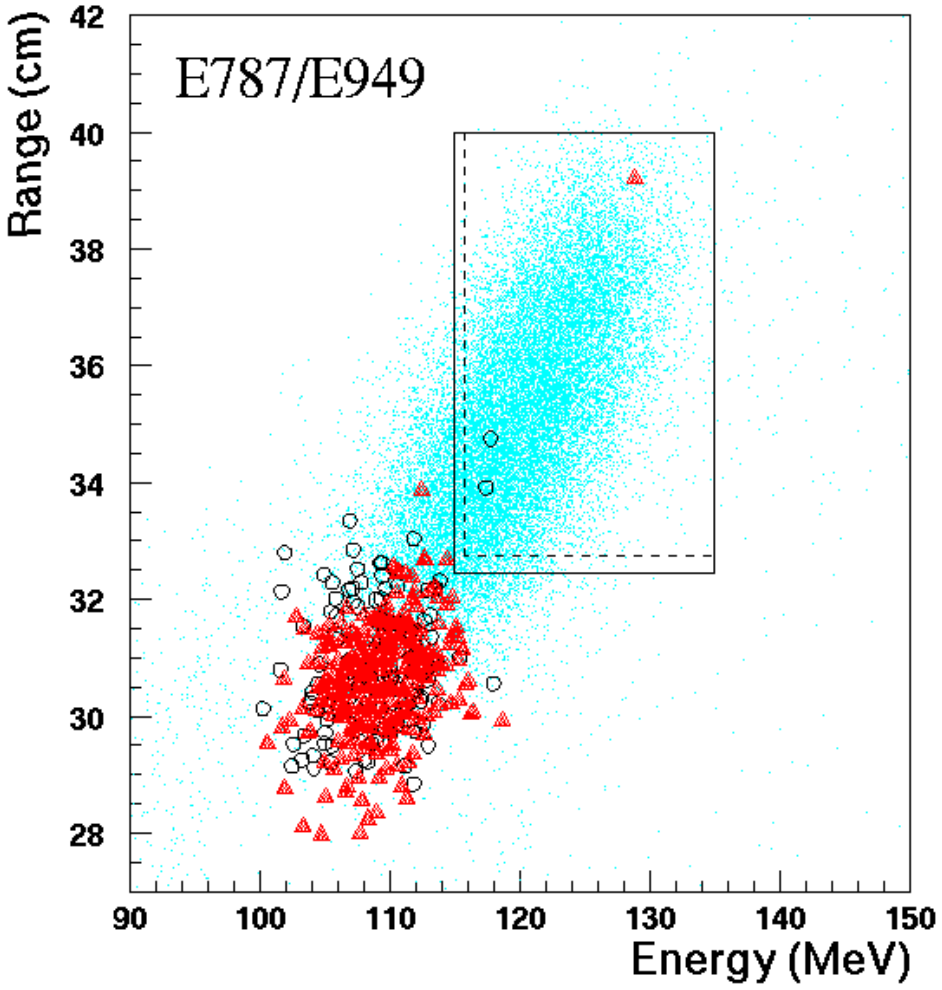
Test correlations

- Change selection criteria
- Move the window

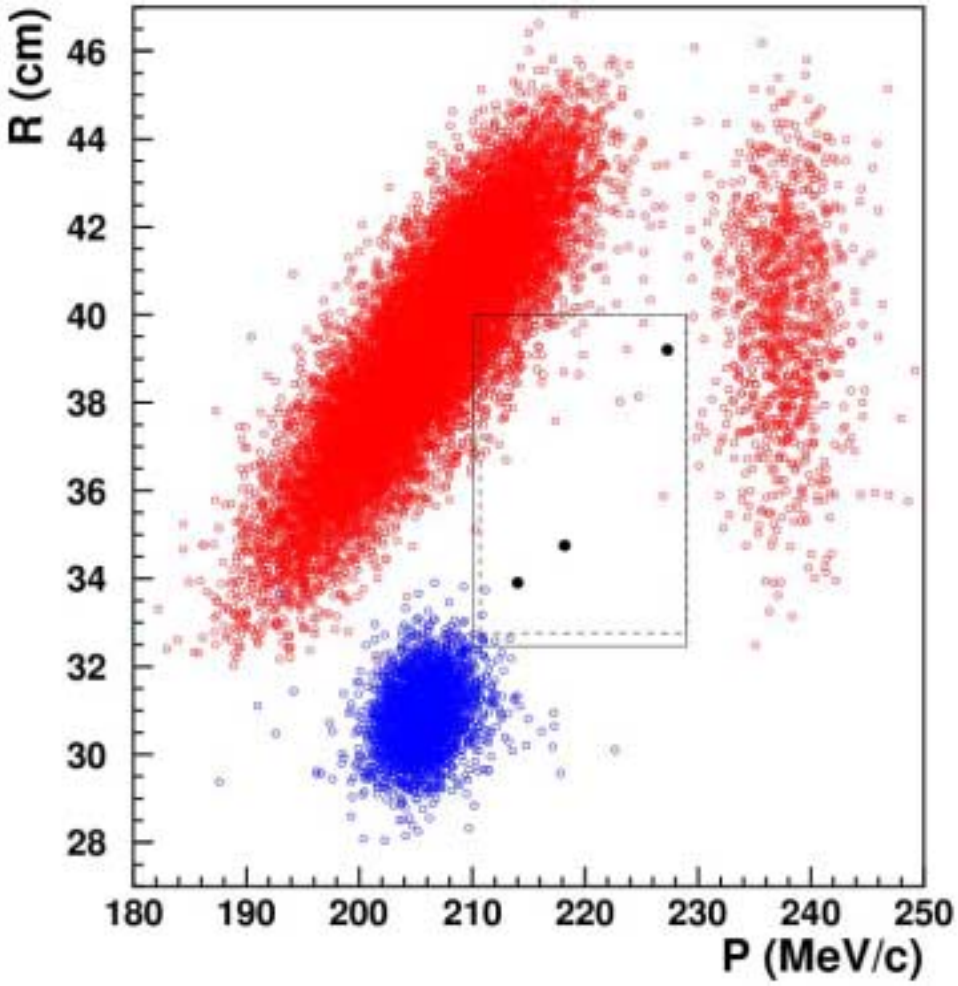


	PV x KIN	10 x 10	20 x 20	20 x 50	50 x 50	50 x 100
Kπ2	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD x KIN	10 x 10	20 x 20	50 x 50	80 x 50	120 x 50
Kμ2	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD x KIN	10 x 10	20 x 20	50 x 20	80 x 20	80 x 40
Kμ2γ	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

E787/E949 combined results

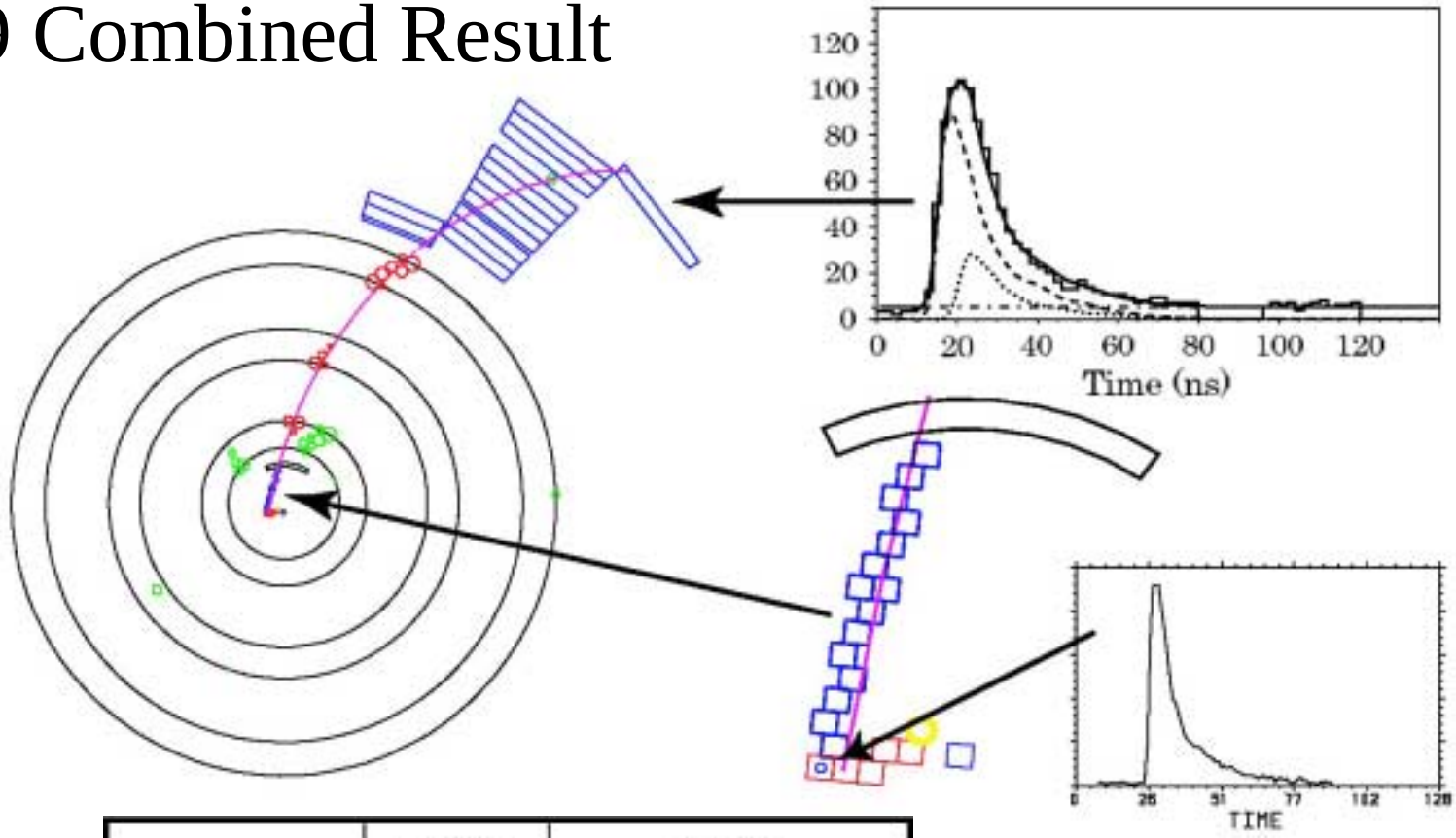


Combined plot of final samples.



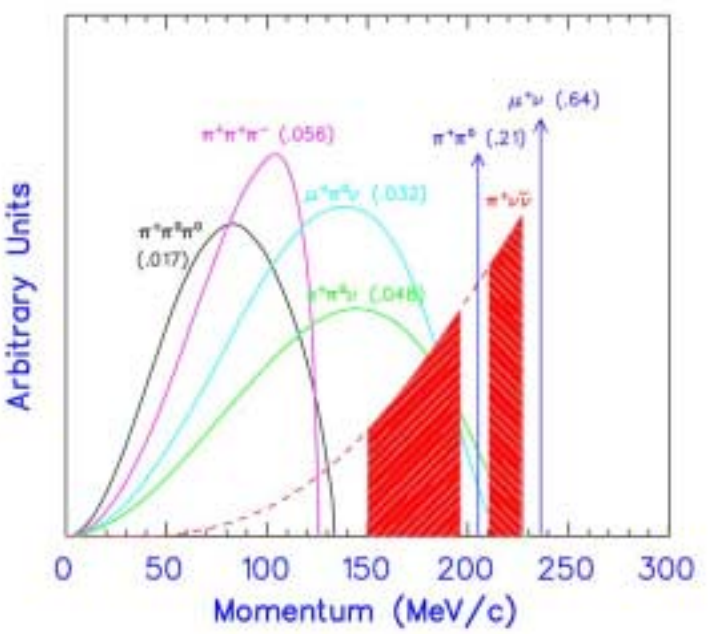
Backgrounds have been enhanced.

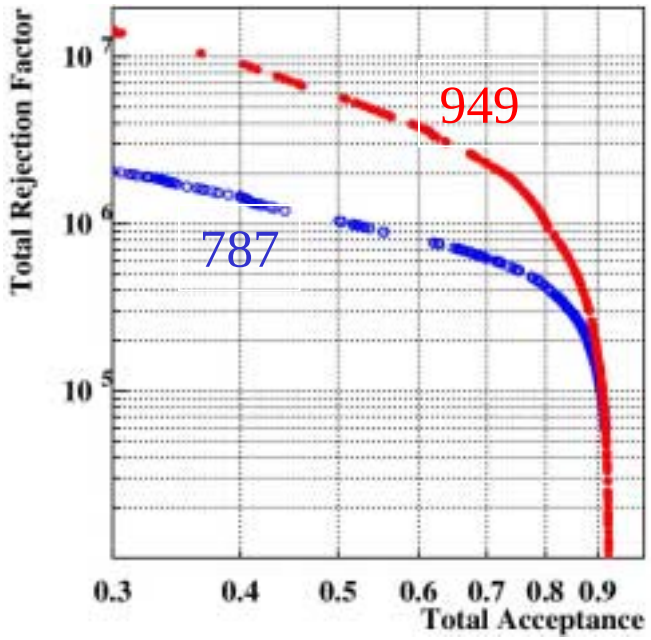
E787/949 Combined Result

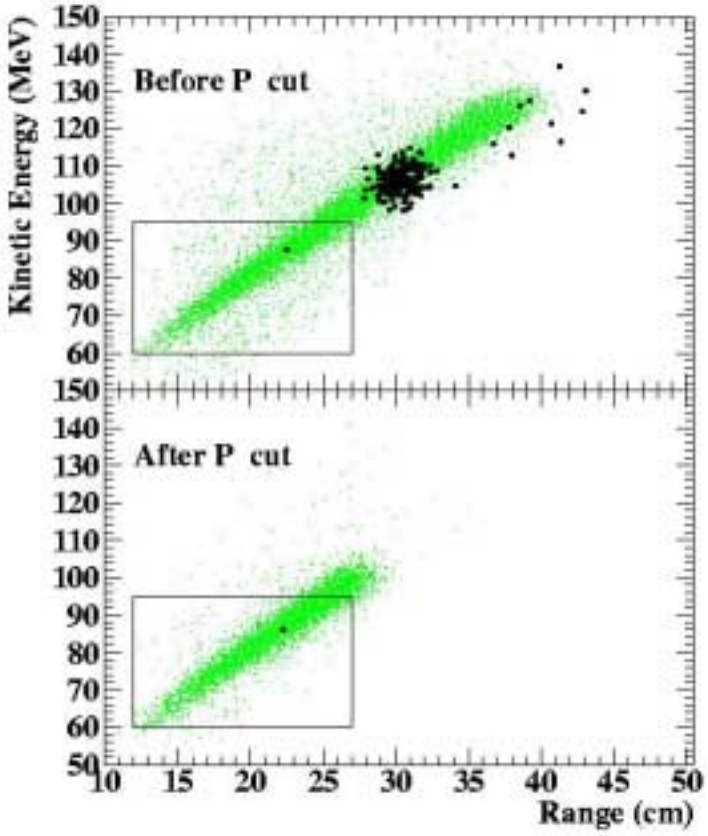


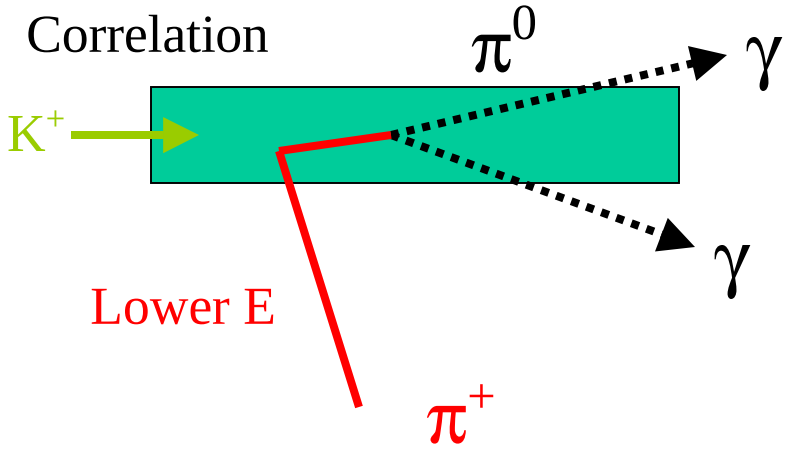
	E949	E787	
Candidate	E949A	E787A	E787C
S_i / b_i	0.9	50	7
W_i	0.48	0.98	0.88
Combined BR	(1.47	$^{+1.30}_{-0.89}$	)$\times 10^{-10}$

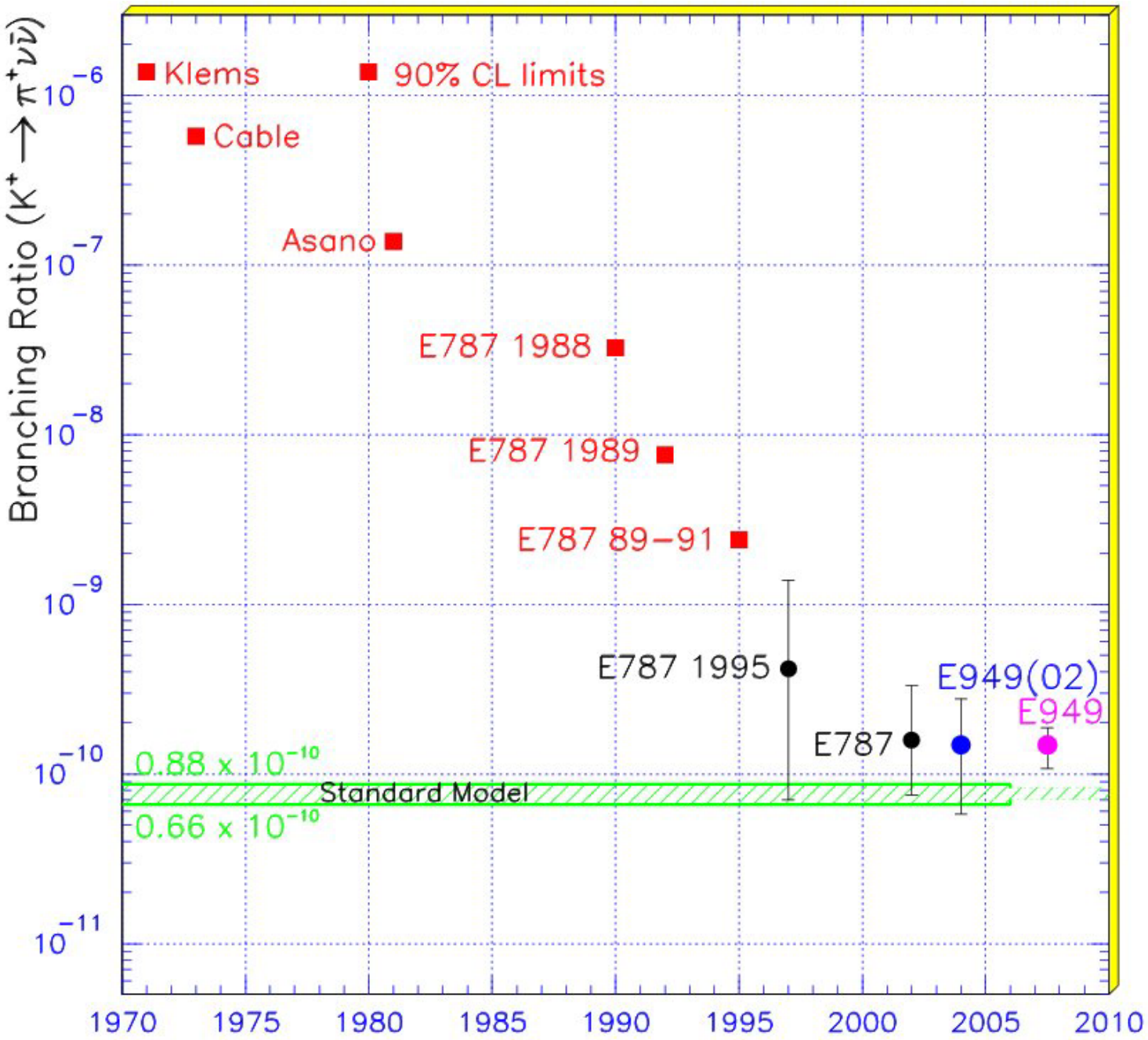
Below the peak









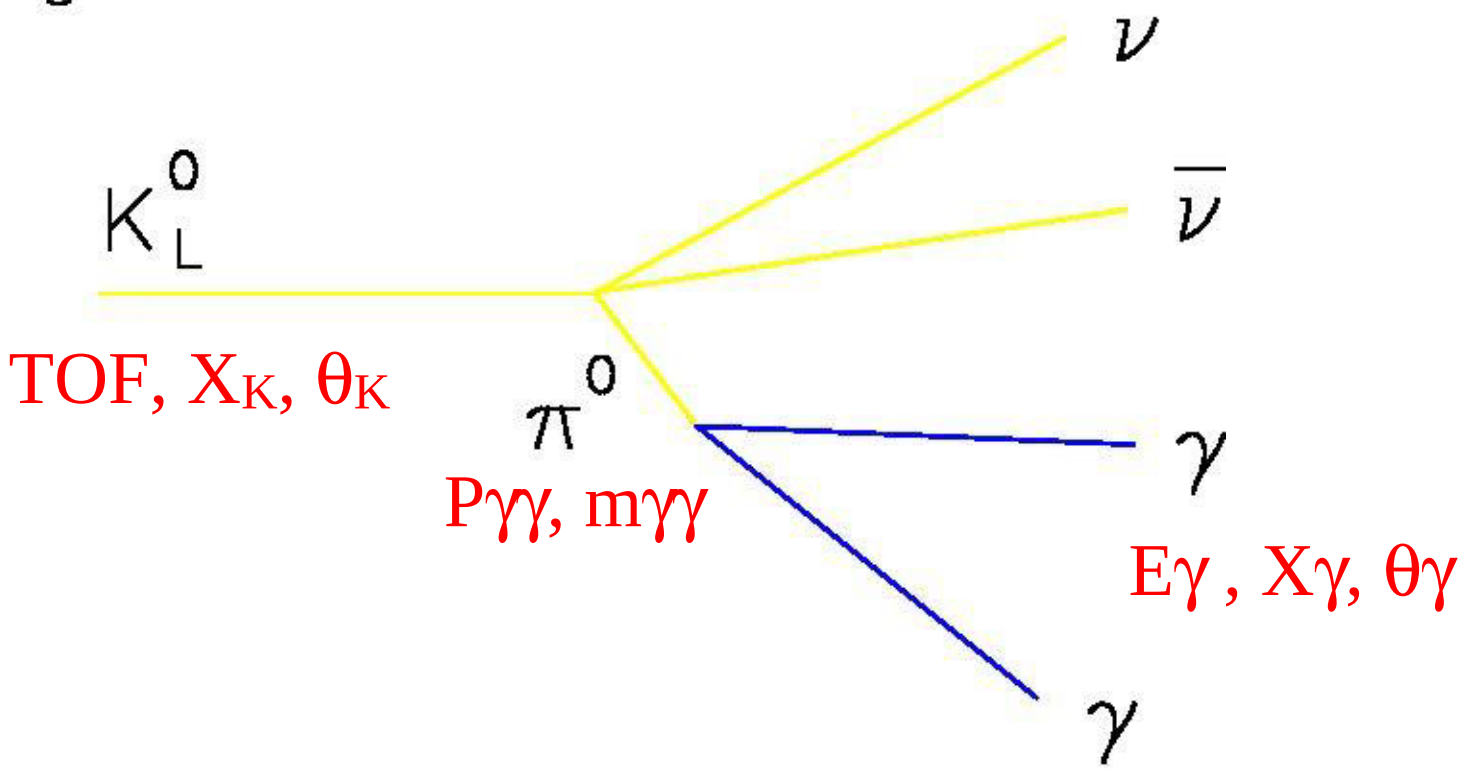

Branching Ratio ($K^+ \to \pi^+ \nu\bar{\nu}$)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Klems
90% CL limits
Cable
Asano
E787 1988
E787 1989
E787 89−91
E787 1995
E787
E949(02)
E949
0.88×10^{-10}
Standard Model
0.66×10^{-10}
1970
1975
1980
1985
1990
1995
2000
2005
2010

Status of E949

- Data were taken in 2002. Upgrade was successful.
- DOE funds stalled.
- $K^+ \rightarrow \pi^+ \nu\nu$ study above the $K_{\pi 2}$ peak: completed.
- $K^+ \rightarrow \pi^+ \nu\nu$ study below the $K_{\pi 2}$ peak: in progress.
- $\pi^0 \rightarrow \nu\nu$ analysis: in progress.
- Analyses of radiative decay modes: in progress.
- Funding for runs from NSF?
- Other experiments using the E949 detector are being considered.

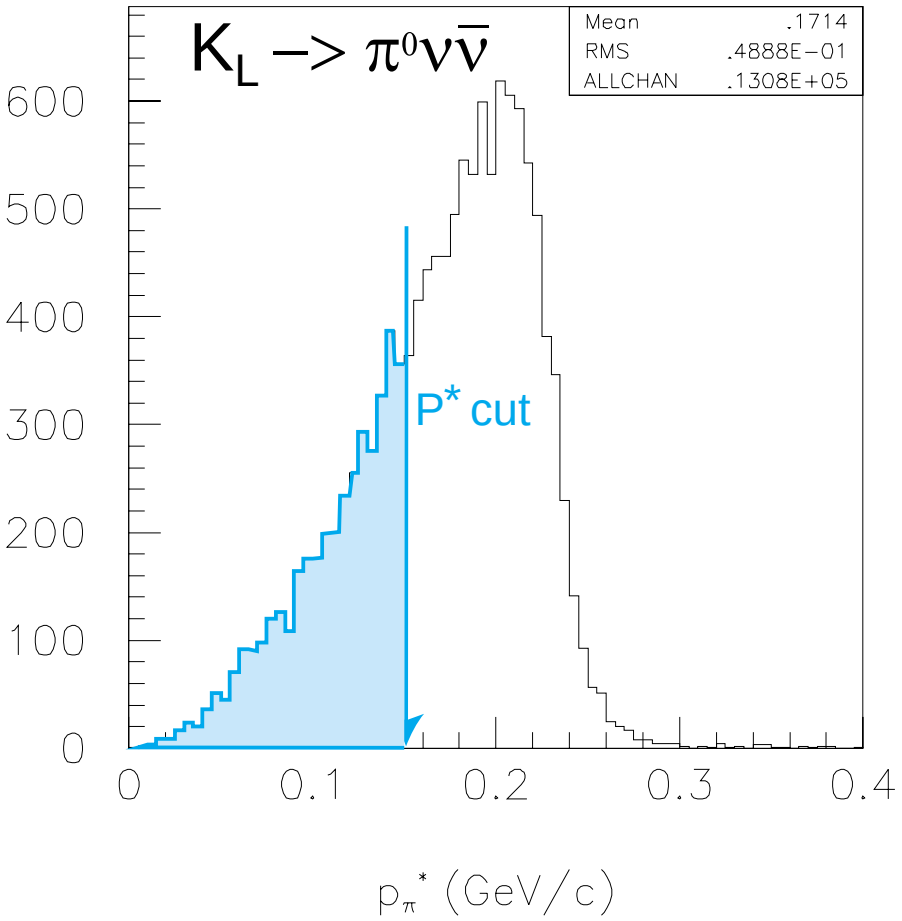
$K_L^0 \to \pi^0 \nu\nu$

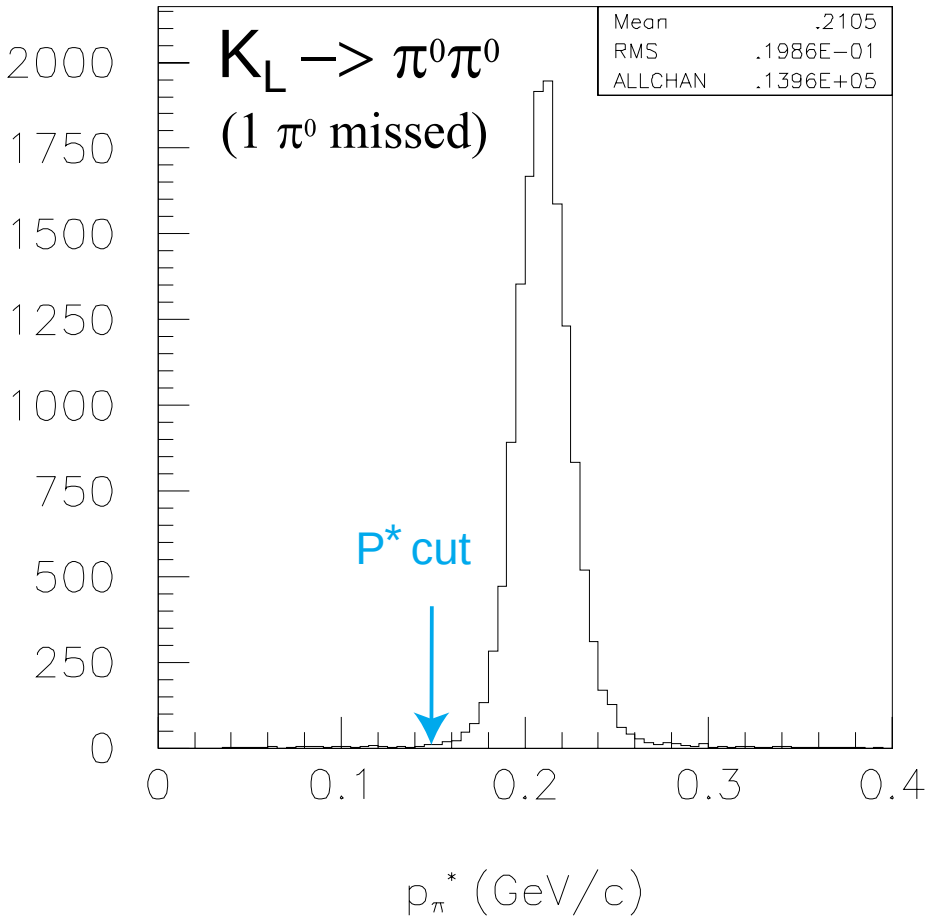
Signature



- 2 γ's
- No other activity

$K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0$ identification





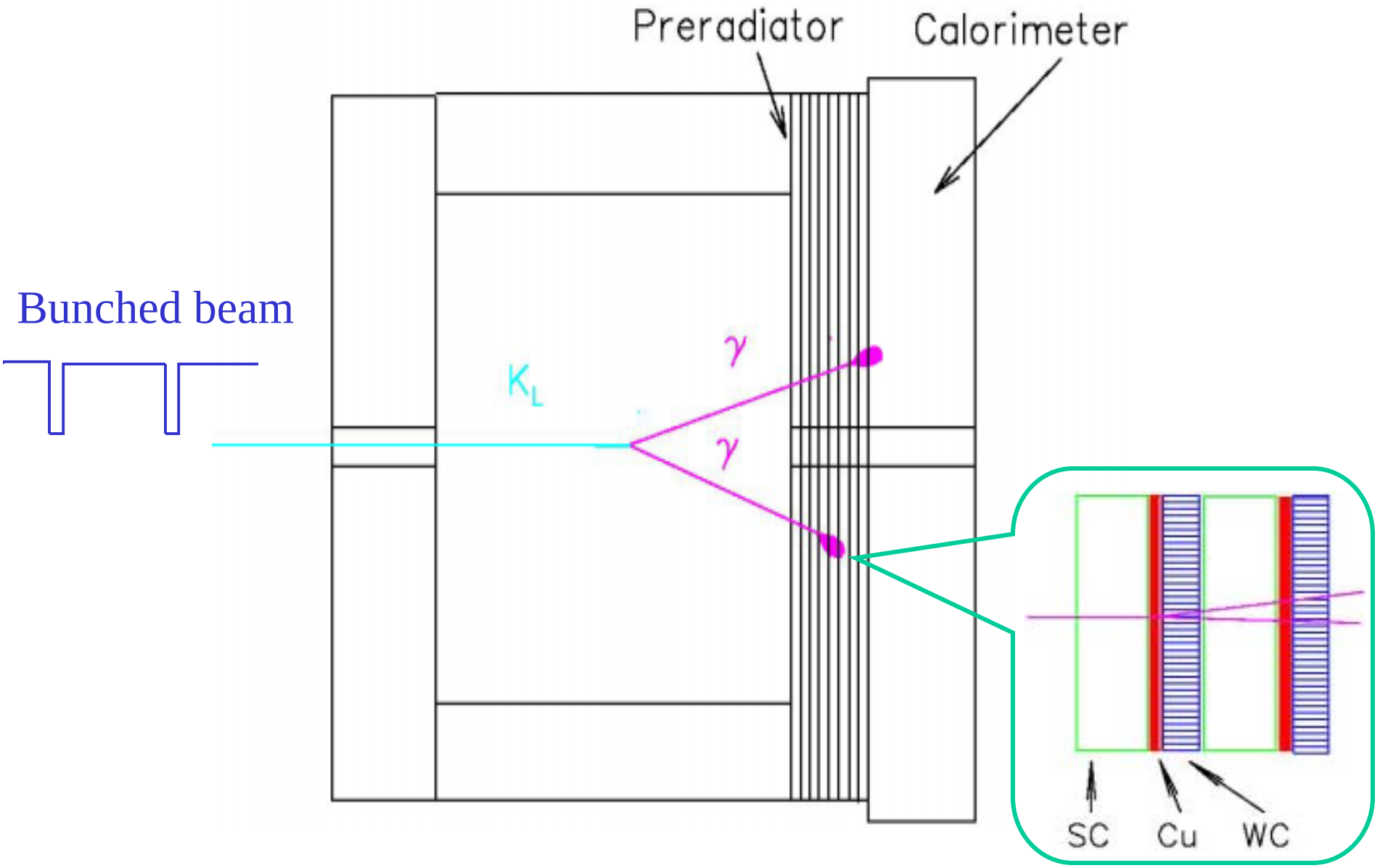
Background sources from K decays

K_L^0 Decay	$\mathcal{B}/3 \times 10^{-11}$	Kinematic	Photon veto	Charged veto
$\pi^0\pi^0$ even	3.1×10^7	E_π^*	$\surd\surd$	
$\pi^0\pi^0$ odd	3.1×10^7	$\lvert E_{1\gamma}^* - E_{2\gamma}^* \rvert$, $M_{\gamma\gamma}$	$\surd\surd$	
$\pi^\pm e^\mp \nu\gamma$	1.2×10^8	$M_{\gamma\gamma}$, χ^2	$\surd$	$\surd$
$\pi^+\pi^-\pi^0$	4.2×10^9	E_π^*, E_{MISS}		$\surd\surd$
$\pi^0\pi^\pm e^\mp \nu$	1.7×10^6	E_π^*		$\surd\surd$
$\pi^0\pi^0\pi^0$	7.0×10^9	E_π^*	$\surd\surd\surd$	
$\pi^0\gamma\gamma$	5.6×10^4		$\surd\surd$	
$\gamma\gamma$	2.7×10^7	$M_{\gamma\gamma}$, E_π^*		

even $\equiv$ both γ from same π^0

odd $\equiv$ γ from different π^0

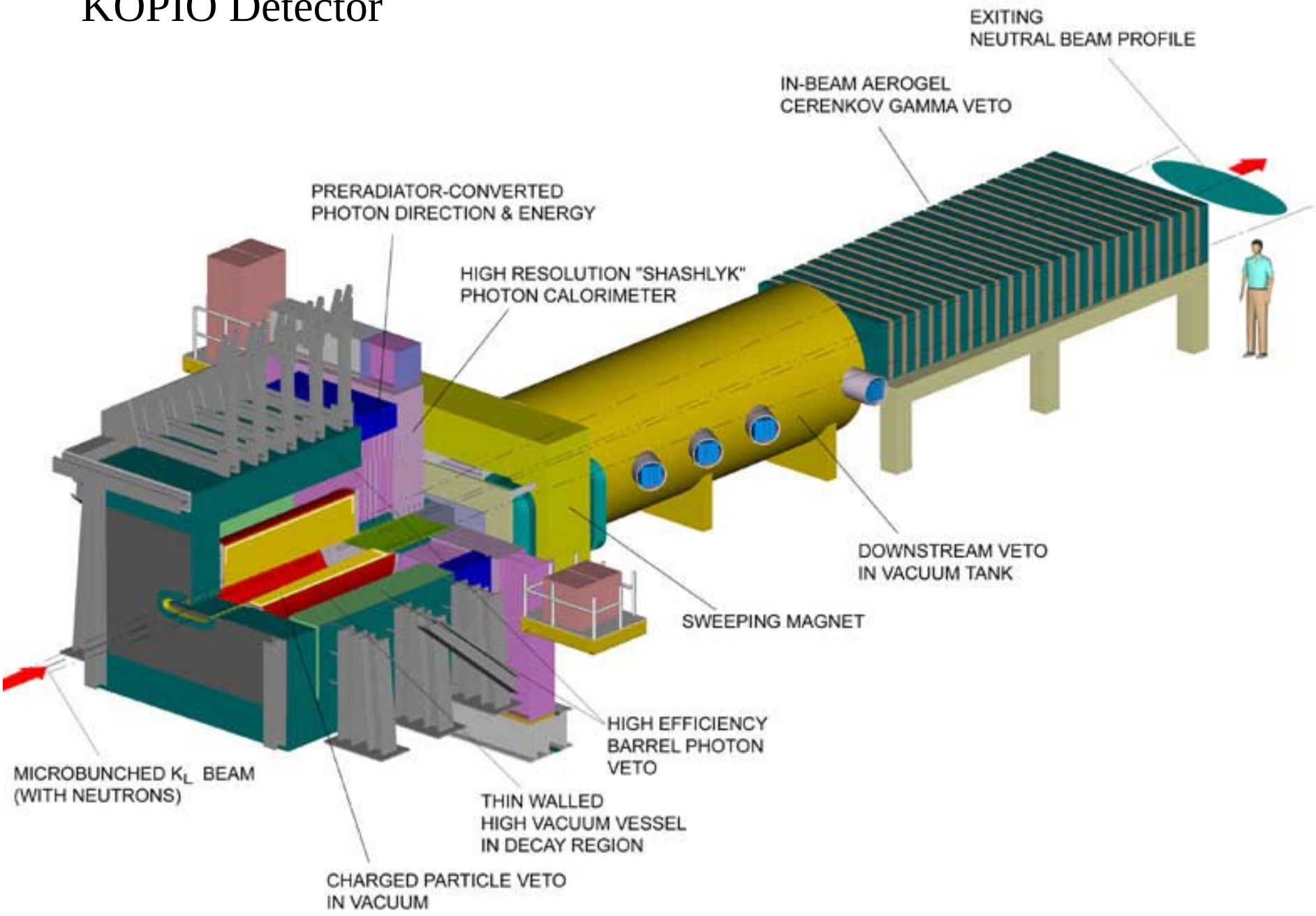
Detection concept



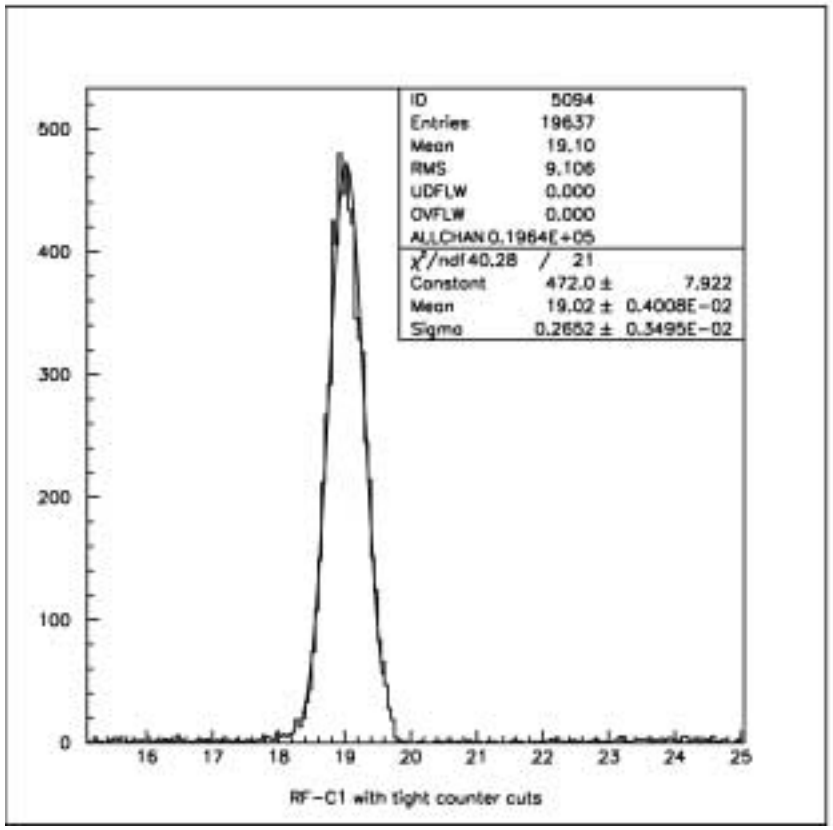
KOPIO Requirements

Parameters	Req.	Expected
ΔE_γ $(E_\gamma^{-1/2})$	3.5 %	2.7 %
$\Delta\theta_\gamma$ (250MeV)	25–30 mr	23 mr
Δt_γ $(E_\gamma^{-1/2})$	100 ps	50 ps
$\Delta x_\gamma, \Delta y_\gamma$	1.0 cm	<0.1 cm
Bunch width	300 ps	200 ps
$\bar{\gamma}$ ineff.	$\bar{\epsilon}_{E787}$	$0.3\cdot\bar{\epsilon}_{E787}$

KOPIO Detector



Beam

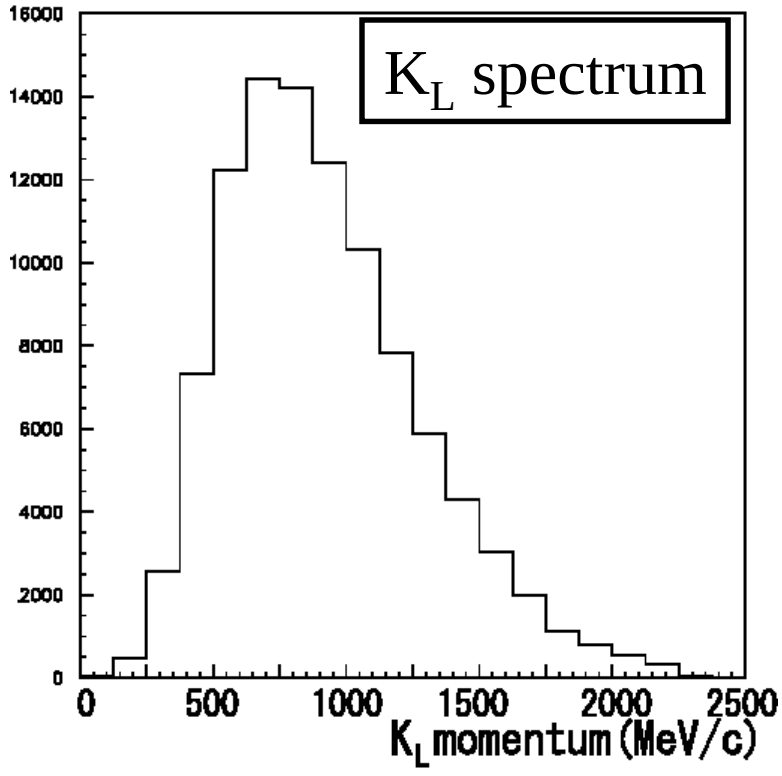


Beam bunch resolution:

Required: 300ps

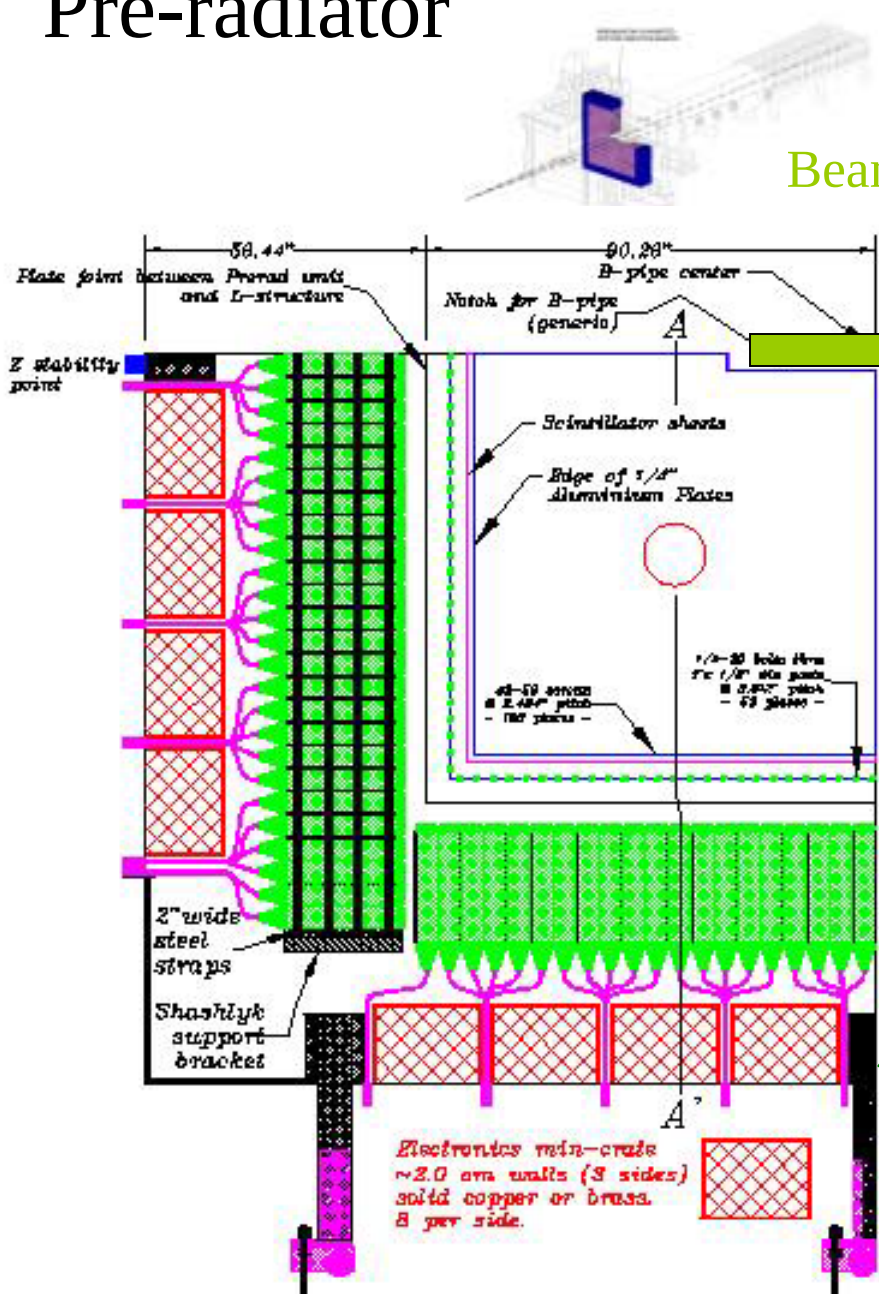
Data: 240ps Sim: 215ps

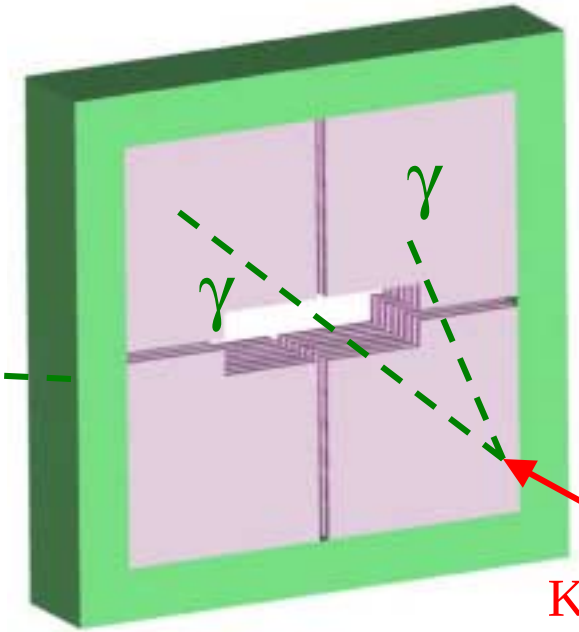
Expected: 181ps



- Neutral Beam
  - Large take-off angle ~ 45degree
  - Low momentum : 0.5 – 1.5 GeV/c to allow TOF measurement
  - Beam size: 5mr(V) x 100mr(H)
  - 3 x 10^8 KL / spill , 12% decay
  - 3.5 x 10^{10} neutrons / spill

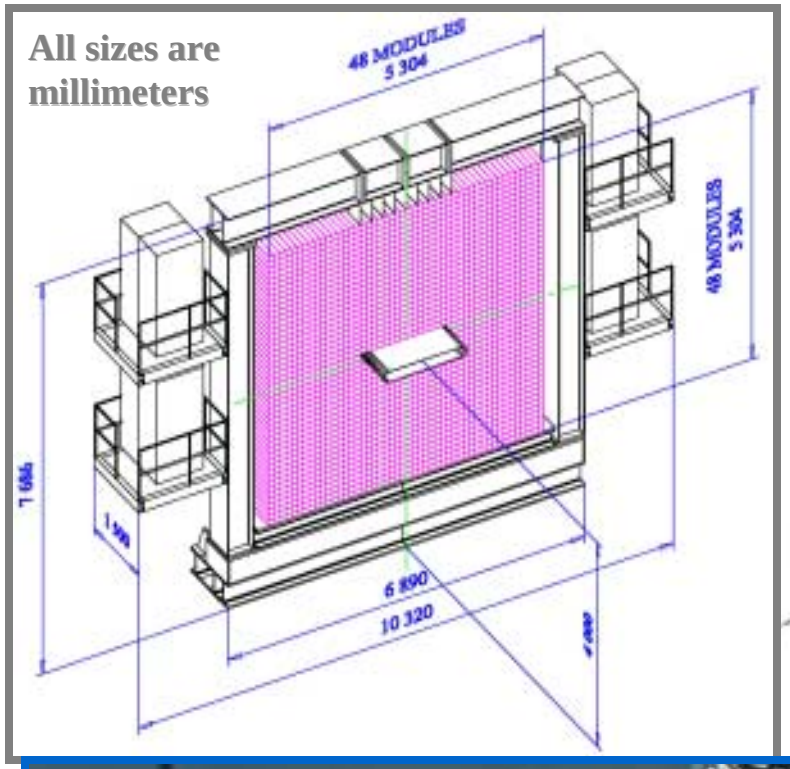
Pre-radiator

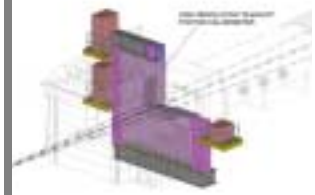


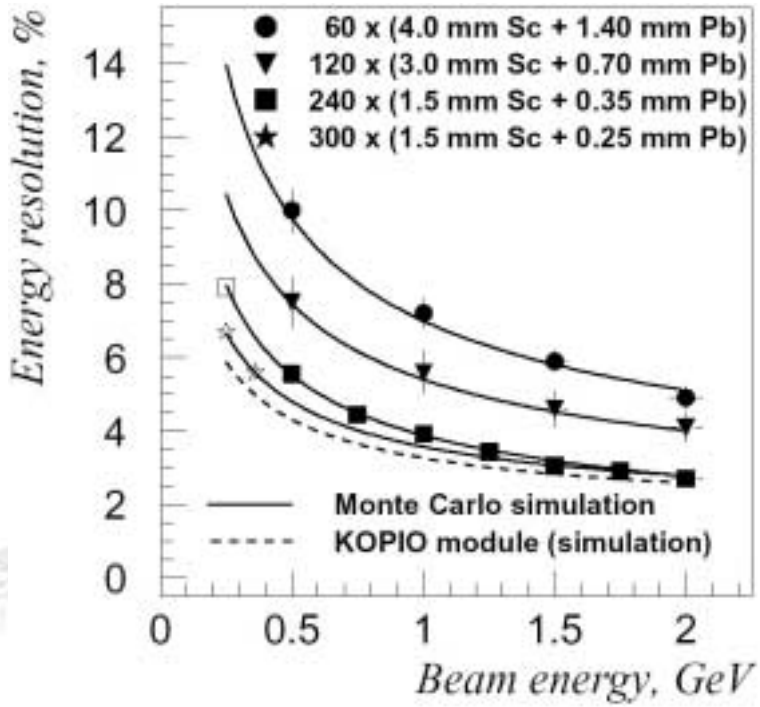


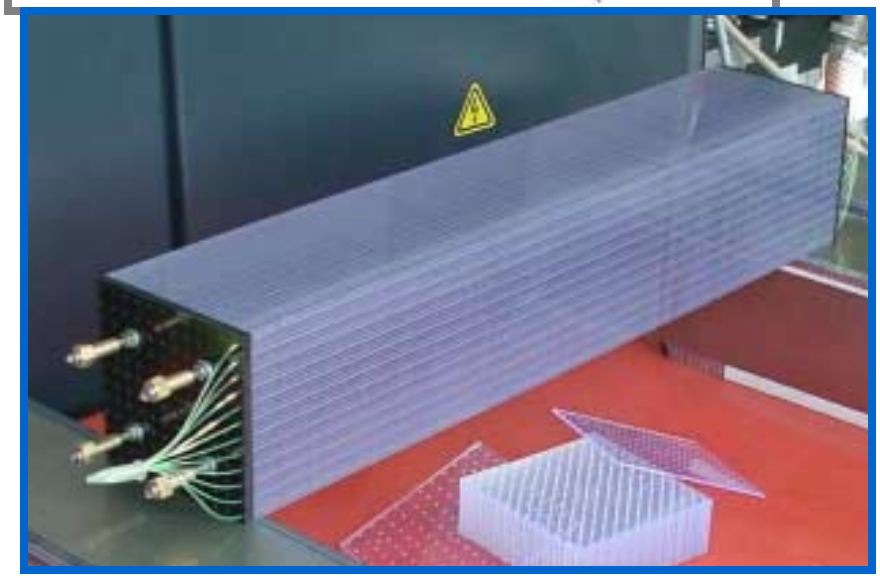
- Task: Measure γ ray direction, Δθ~25mr
- Total radiation length: ~ 2 (64 layers)
- Each layer: scintillator, X-Y chamber
- Consists of four 2x2m² quadrants
- Surrounding PV system

Calorimeter





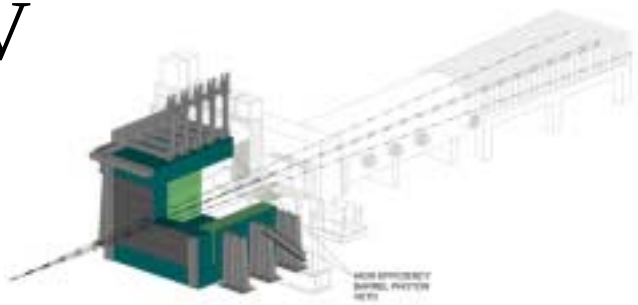


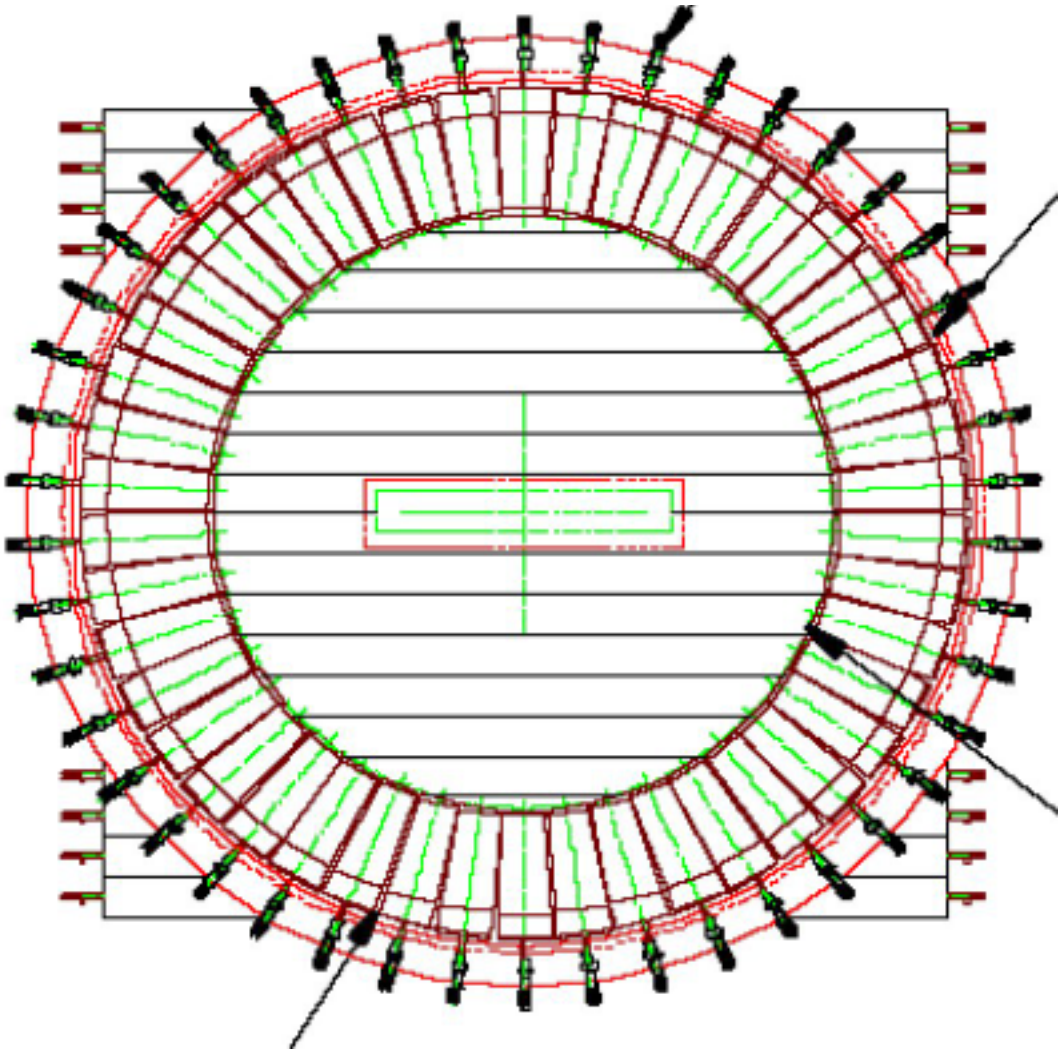


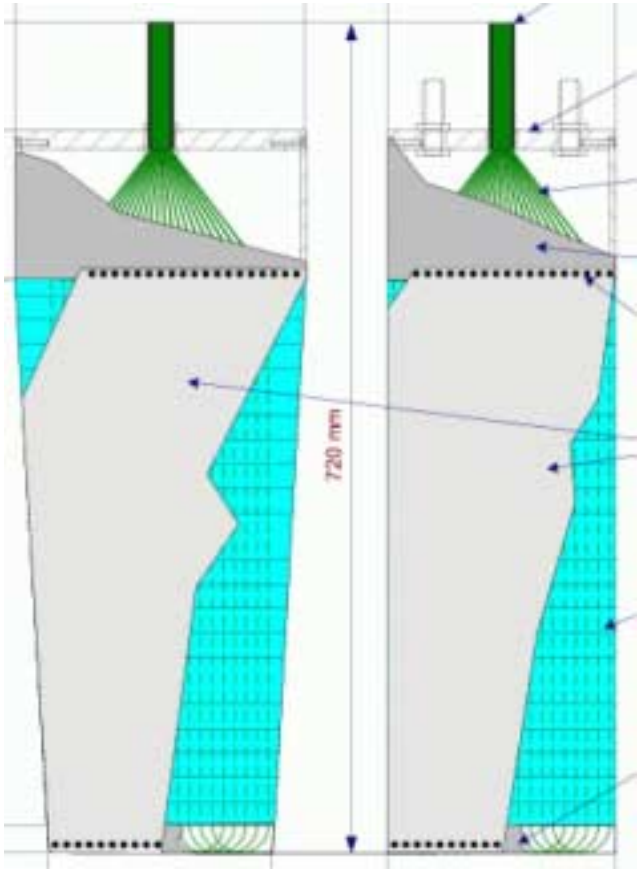
Size: 5.3m x 5.3m
Granularity: 11cm x 11cm
Radiation length: 16 X_0
Pb thickness: 0.275 mm
Scintillator: 3.5 mm
# of layers: 300

$\Delta E = 2.9 \pm 0.1$ %/sqrt(E(GeV))
$\Delta T = 90 \pm 10$ ps/ sqrt(E(GeV))
(from early prototype)

Barrel PV

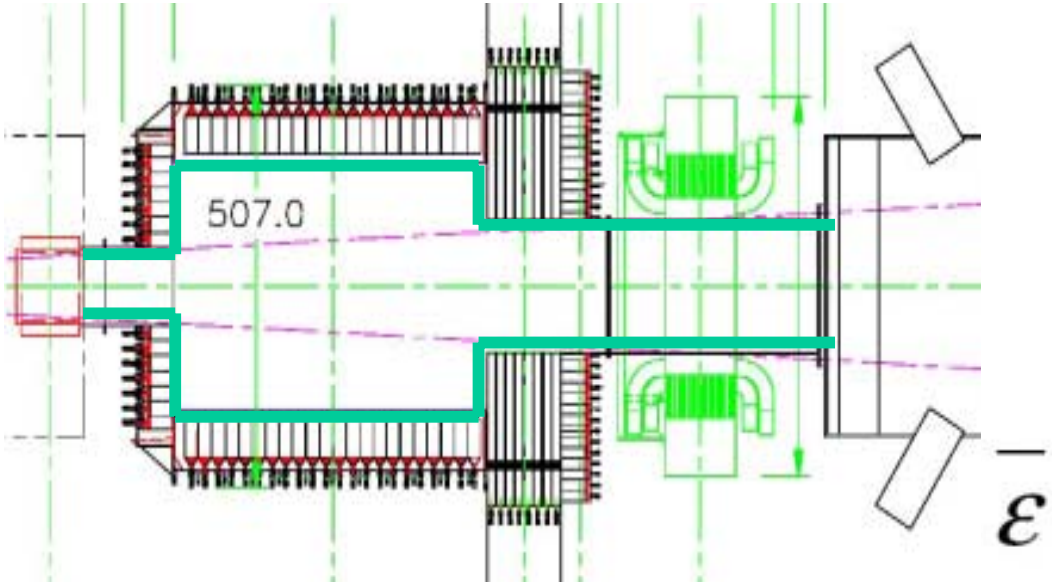


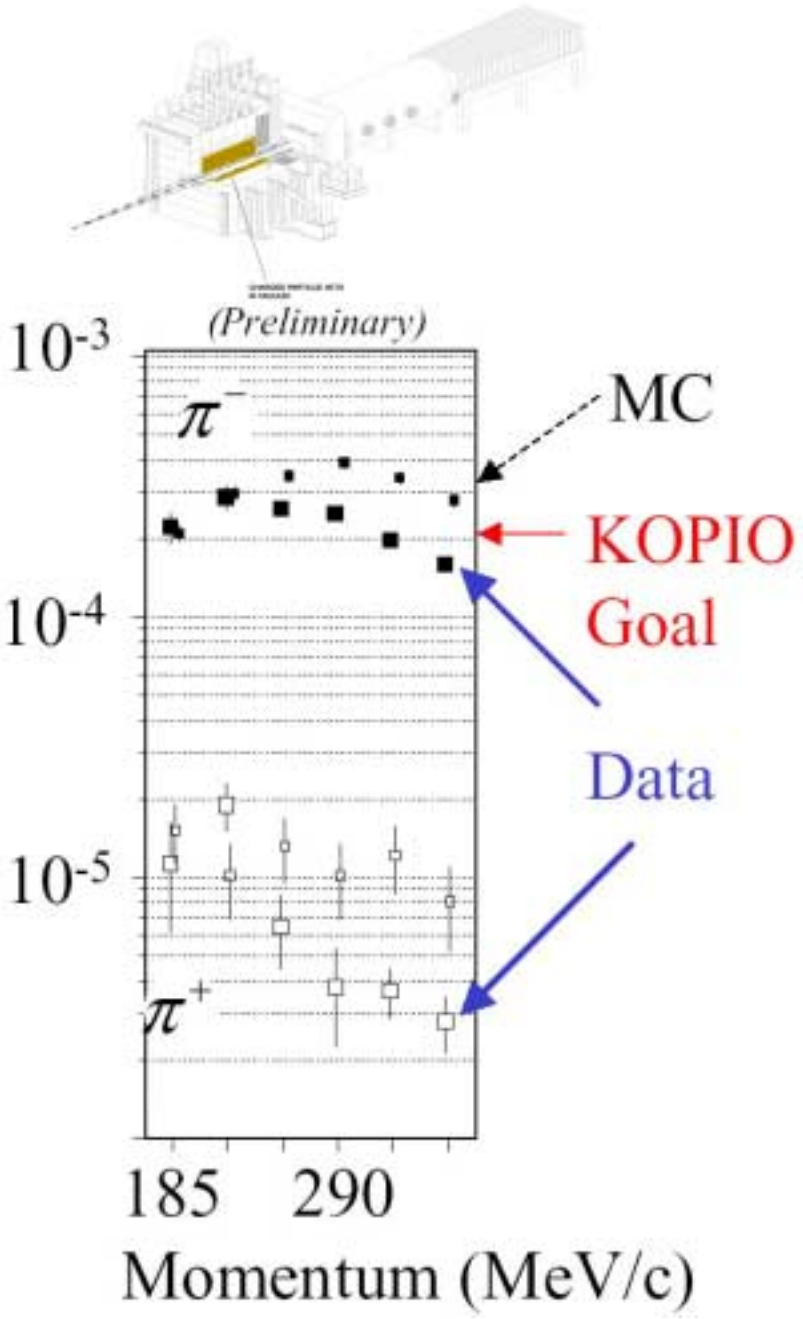




Shashlyk modules: ~1000
Inefficiency (100MeV): 2×10^{-4}
Time resolution(1GeV): 70-90ps

Charged particle veto





Major decay modes: $K_L \rightarrow \pi\mu\nu$

$\pi e\nu$

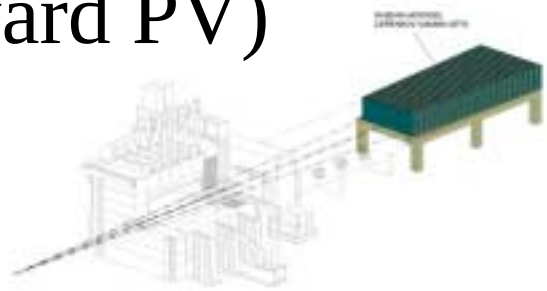
$\pi\pi\pi$

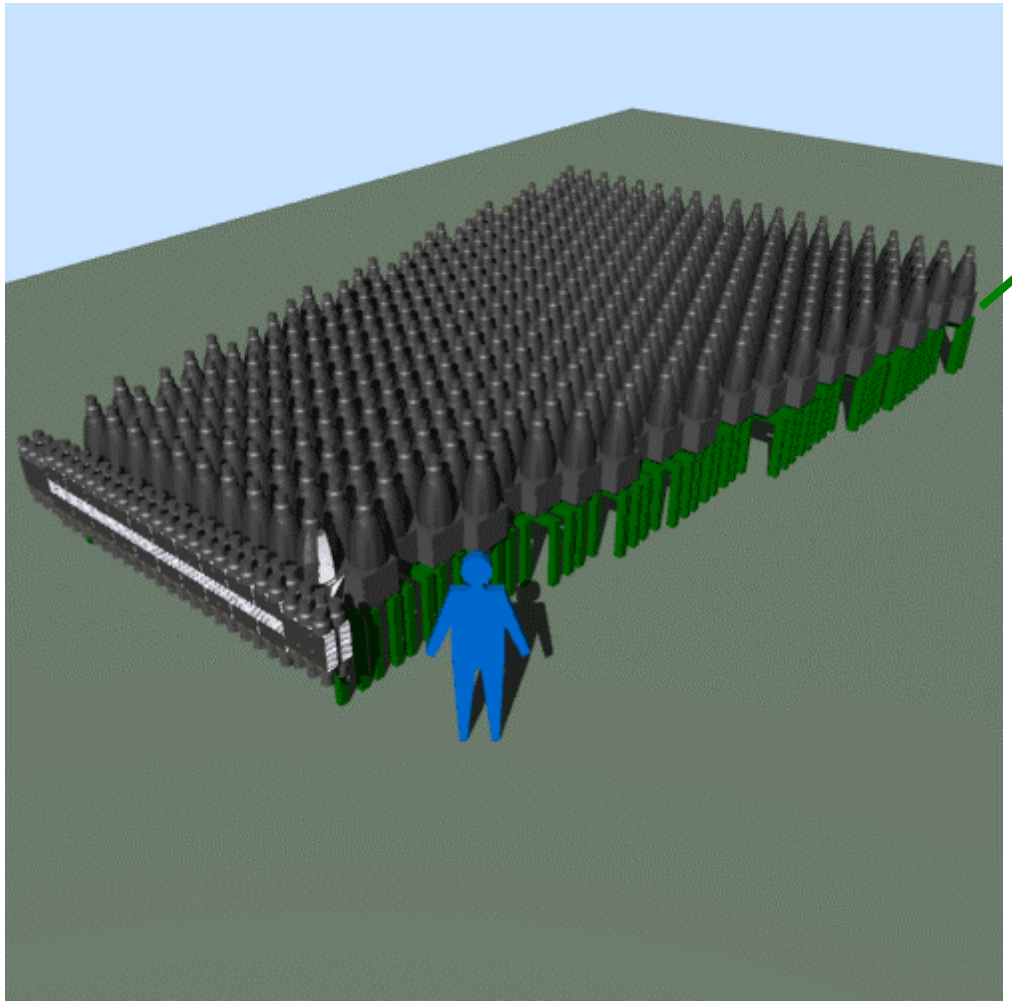
$e^+ \rightarrow \gamma$ and $\pi^- p \rightarrow \pi^0 n$

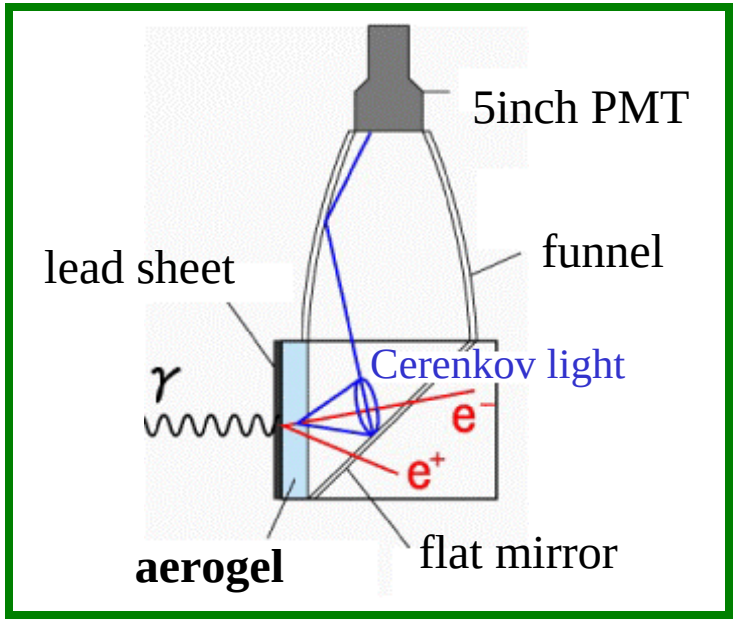
Inefficiency:

e^+	$< 10^{-4}$
π^-	$< 10^{-4}$
other	$< 10^{-5}$

Catcher (Forward PV)

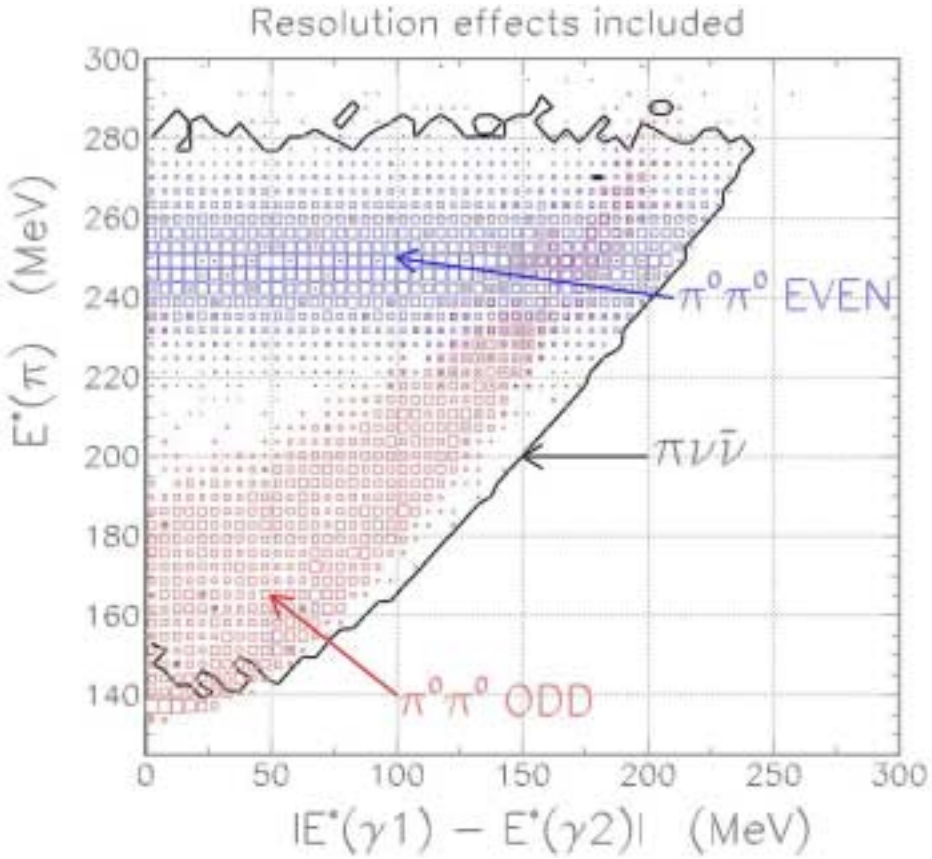


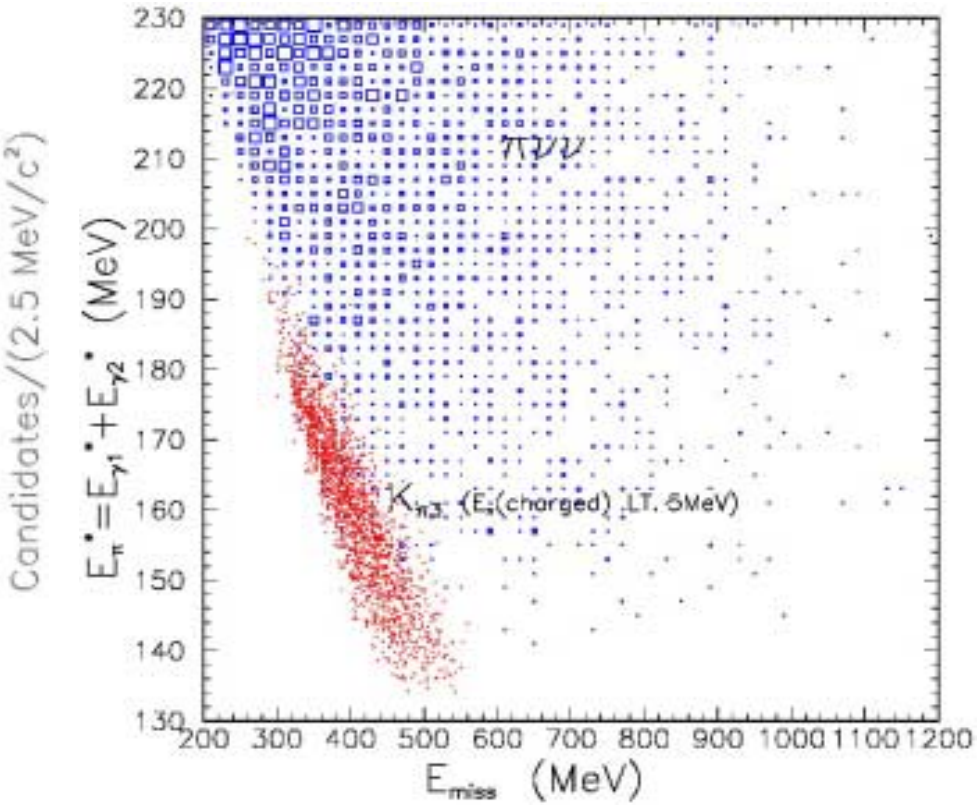




- Module size: 30cm x 20cm
- # of modules: 370
- # of layers: 25 (8.3 X_0)
- Pb thickness: 2mm
- Forward beam hole counters
- Pb/aerogel tile counters
- $\varepsilon_\gamma > 99\%$ (0.3GeV/c)
- Insensitive to slow particles
- $\varepsilon_n < 0.3\%$ (0.8GeV/c)

Examples of background distributions

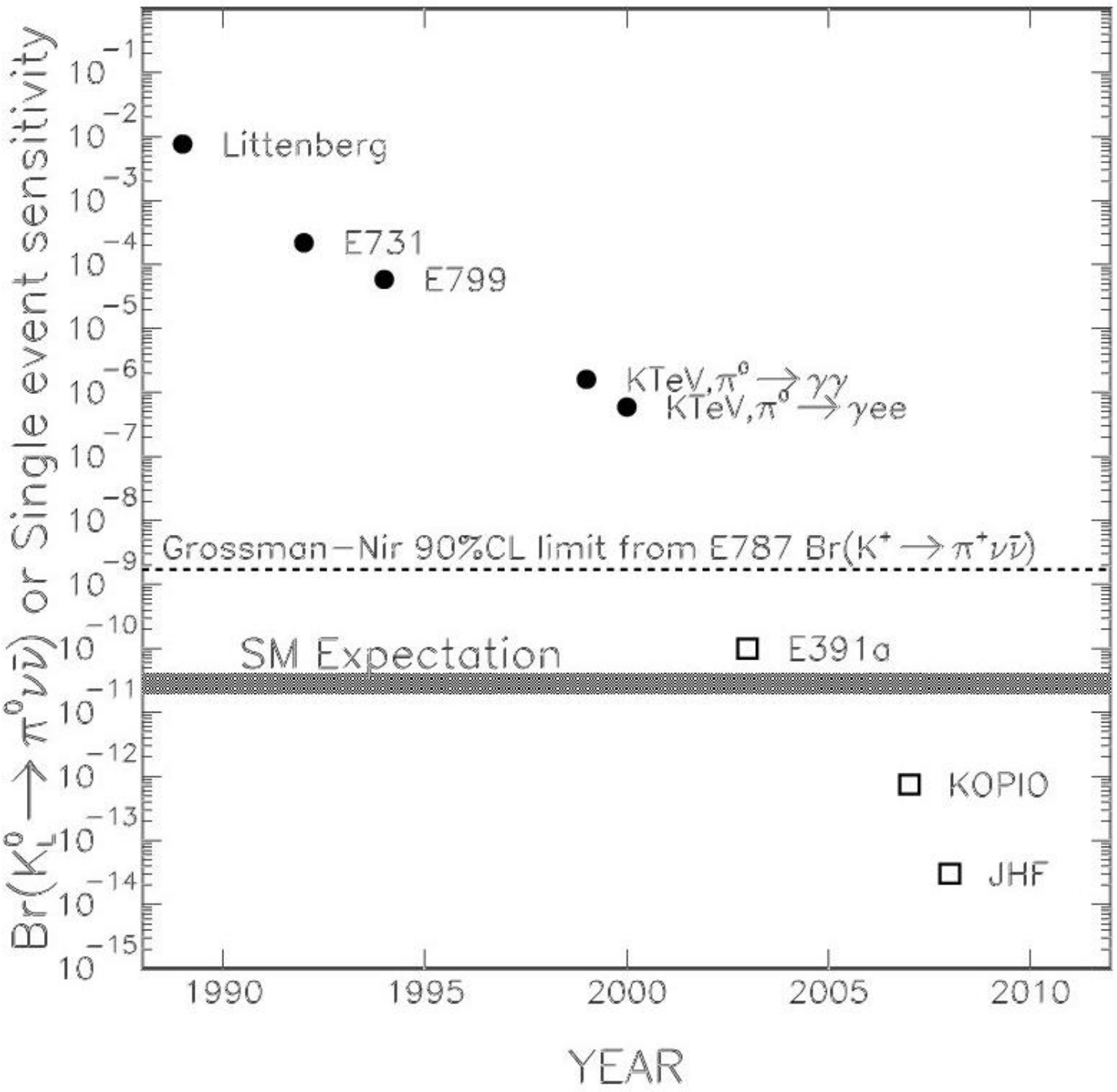




Process	Events
$K_L^0 \to \pi^0 \nu\bar{\nu}$ at SM rate	40
$K_L^0 \to \pi^0\pi^0$	12.4
$K_L^0 \to \pi^\pm e^\mp \nu\gamma$	4.5
$K_L^0 \to \pi^-\pi^+\pi^0$	1.7
$K_L^0 \to \pi^\pm e^\mp \nu$	0.02
$K_L^0 \to \gamma\gamma$	0.02
$\Lambda \to \pi^0 n$	0.01
Interactions ($nN \to \pi^0 X$)	0.2
Accidentals	0.6
Total Background	19.5

Status of the Experiment

- Approved by NSF in 2003.
- $6M R&D funds in FY04.
- $30M for RSVP in the 2005 president's budget.
- House approved.
- KOPIO schedule
  - 2004 Detector R&D
  - 2005 – 2006 Construction of beam line.
  - 2006 – 2008 Construction and Installation of the detector.
  - 2009 ~ Engineering run
    Physics run


Br($K_L^0 \to \pi^0\nu\bar{\nu}$) or Single event sensitivity
YEAR
Littenberg
E731
E799
KTeV, $\pi^0 \to \gamma\gamma$
KTeV, $\pi^0 \to \gamma ee$
Grossman−Nir 90%CL limit from E787 Br($K^+ \to \pi^+\nu\bar{\nu}$)
SM Expectation
E391a
KOPIO
JHF
1990
1995
2000
2005
2010